eRD6 Progress Report

EIC GENERIC DETECTOR R&D ADVISORY COMMITTEE MEETING

January 24, 2019

Bob Azmoun (BNL)
On Behalf of eRD6

The eRD6 Consortium

- EIC detector R&D for the development of tracking and pID capabilities beyond the present state of the art

  - Brookhaven National Laboratory (BNL)

    People: E.C Aschenauer, B. Azmoun, A. Kiselev, J. Kuczewski, M. L. Purschke, C. Woody

    R&D: Mini-Drift detector; TPC/Cherenkov prototype (TPC-C); MPGD-based TPC; Zigzag pad development (*not funded under eRD6, but relevant for eRD6 R&D*)

  - Florida Institute Of Technology (FIT)

    People: M. Bomberger, M. Hohlmann

    R&D: Large & low mass GEM with zig-zag readout structures; Cylindrical μRWELL

  - INFN Trieste

    People: S. Dalla Torre, S. Levorato, F. Tessarotto

    R&D: Development of hybrid MPGDs for single photon detection, synergistic to TPC read-out sensors (in particular, high momentum RICHes)

The eRD6 Consortium

- ❖ Stony Brook University (SBU)

  People: K. Dehmelt, A. Deshpande, P. Garg, T.K. Hemmick

  R&D: Short radiator length RICH; Large mirror coating, TPC-IBF studies

- ❖ Temple University (eRD3 merger with eRD6)

  People: B. Surrow, M. Posik, A . Quintero

  R&D: Commercial GEMs, MPGD-based trackers, tracking simulations; Cylindrical μRWELL

- ❖ University Of Virginia (UVa)

  People: K. Gnanvo, N. Liyanage

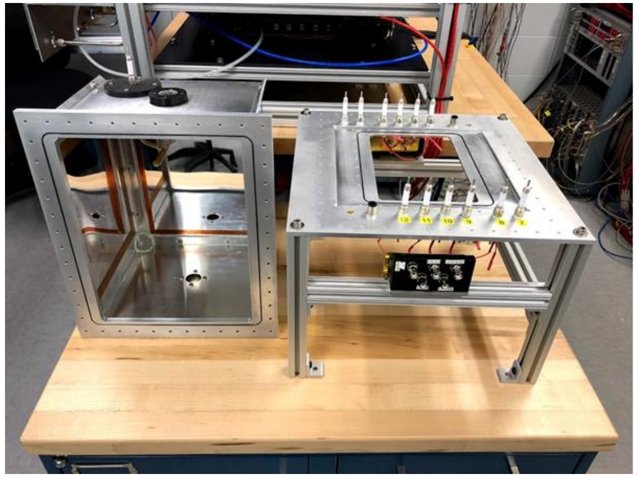
  R&D: Large GEM with U-V readout; Chromium-GEM (Cr-GEM); Cylindrical μRWELL

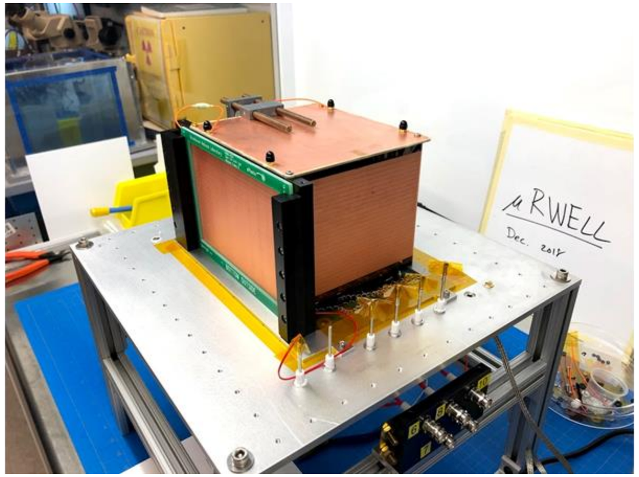
- ❖ Yale University

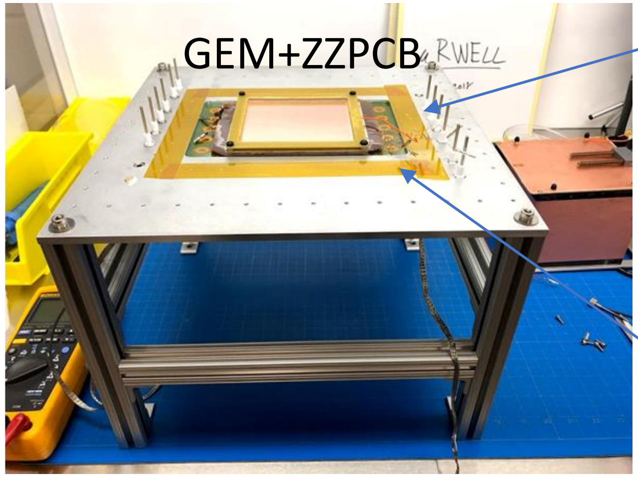
  People: D. Majka, N. Smirnov

  R&D: TPC characterization studies

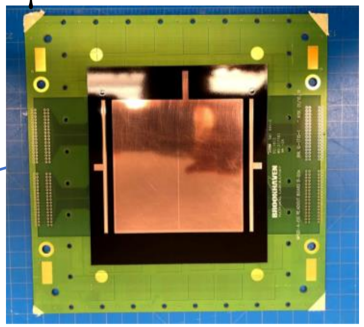
Progress @ BNL:TPC prototype



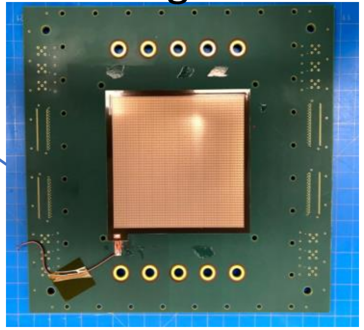




μRWELL+ZZPCB



Micromegas+ZZPCB

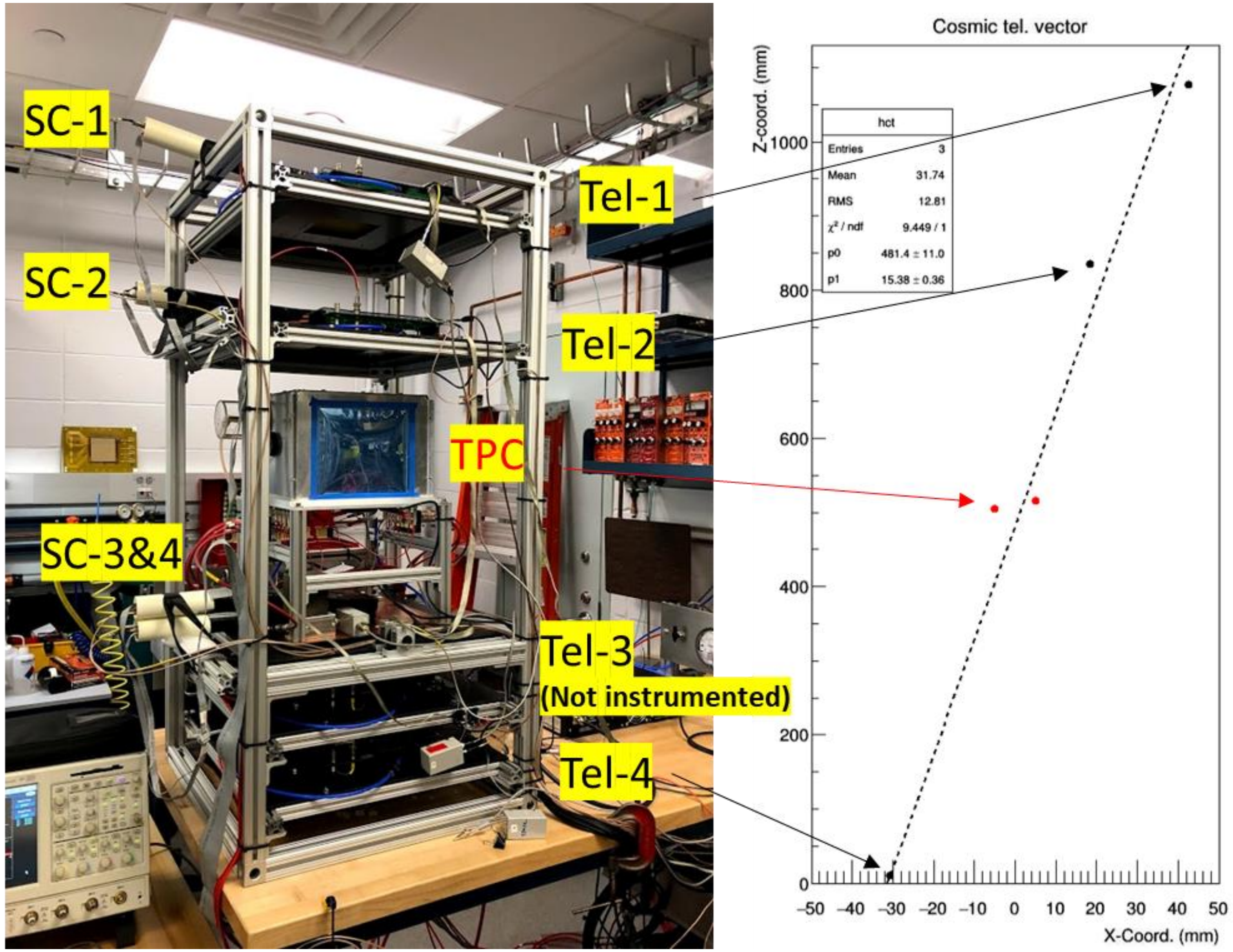


- Assembly and commissioning of new TPC prototype completed (gas tightness, HV tests, etc)
- Re-used TPCC field cage
- 4GEM with optimized zigzag readout
- New flexible and compact design with three large windows
- Tested successfully with cosmics using SRS/APV25 readout FEE (700ns DAQ frame → only measure fraction of charge in TPC)
- For initial tests: Ar-CO_2 (70-30) with drift field of 0.75kV/cm → drift velocity = 25μm/ns
- Eventually will test with μRWELL and MM (initially will test each in a simple planar det. config.)

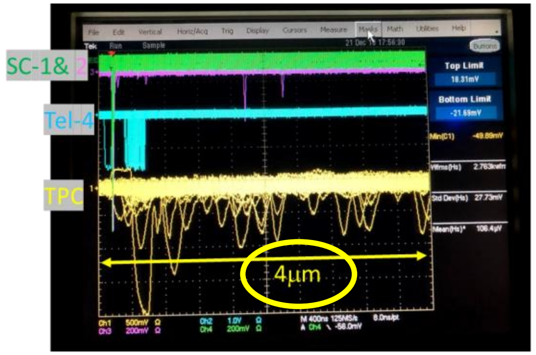
Progress @ BNL:Cosmic-ray telescope

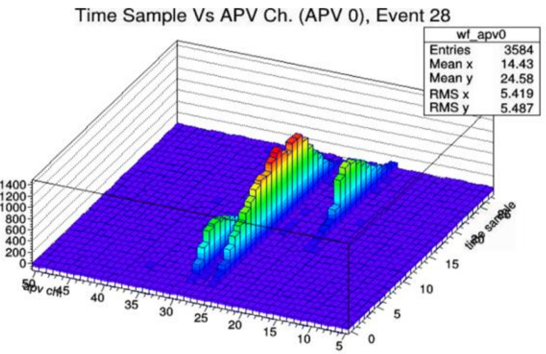
- 4-layers of 3-GEM with COMPASS X-Y r/o
- Commissioned at beam test by UVA
- Coincident signal from 4 scintillator counters provides prompt trigger
- TPC prototype as Det. Under test (for position resolution measurements)
- Expect 40-50μm per telescope layer and 40-50μm/sqrt(4 points) = 25-30μm track pos. resolution

Example of a single reconstructed track



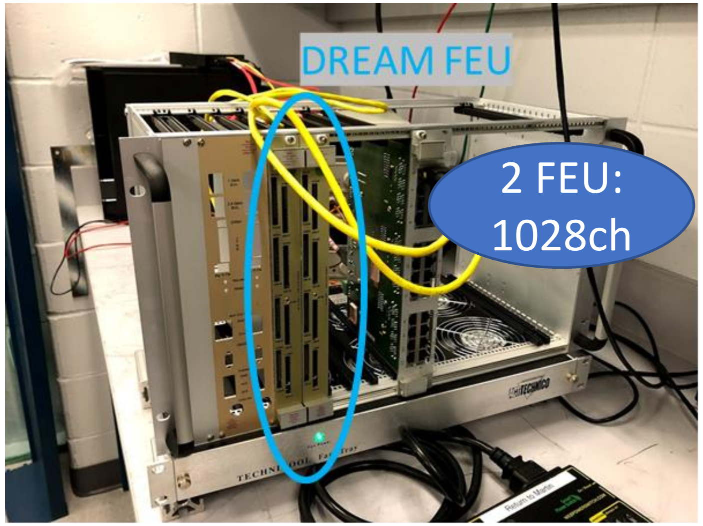
Measured TPC signals span the expected drift time

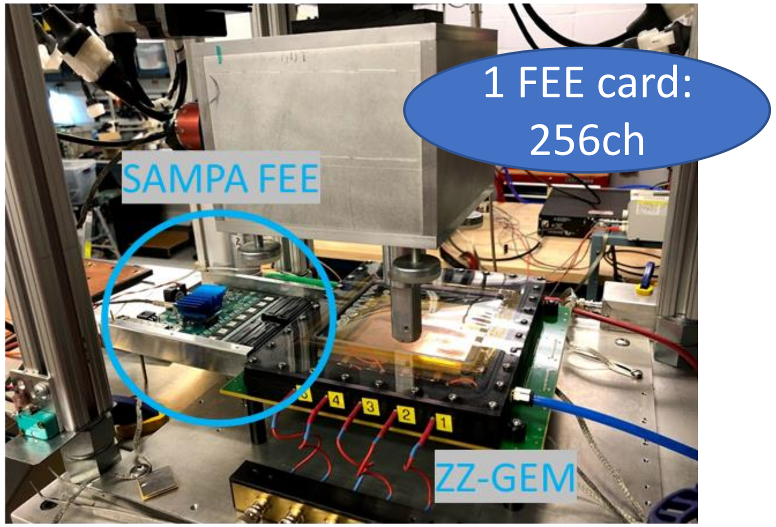




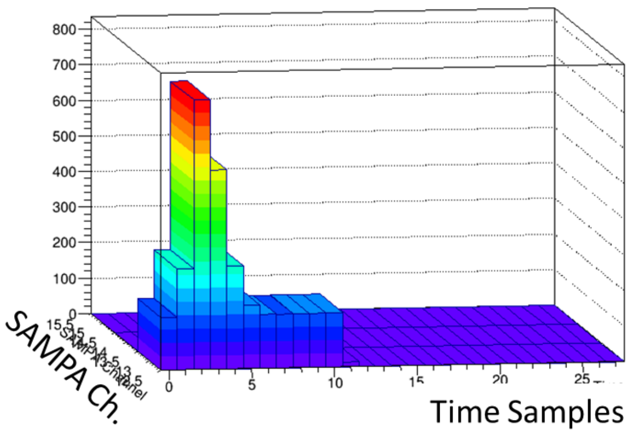
Progress @ BNL:Electronics for TPC r/o

- SAMPA electronics under development: multi-SAMPA chip ASIC + data module card + firmware (continuous and trigger mode)
- Being tested in the lab using a 4GEM w/ ZZ r/o with very positive results (1024 samples @ 10-20MHz ADC)
- DREAM electronics also available: used successfully at beam test last year for measuring ZZ r/o (512 samples @ 1-50MHz ADC)

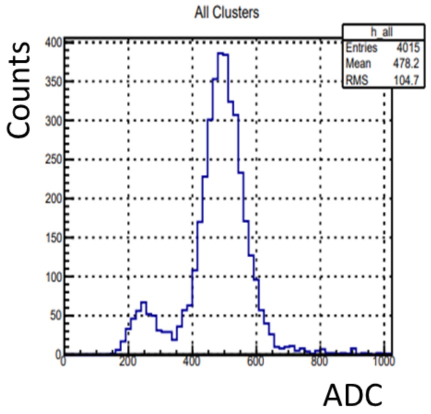




SAMPA Single event waveforms

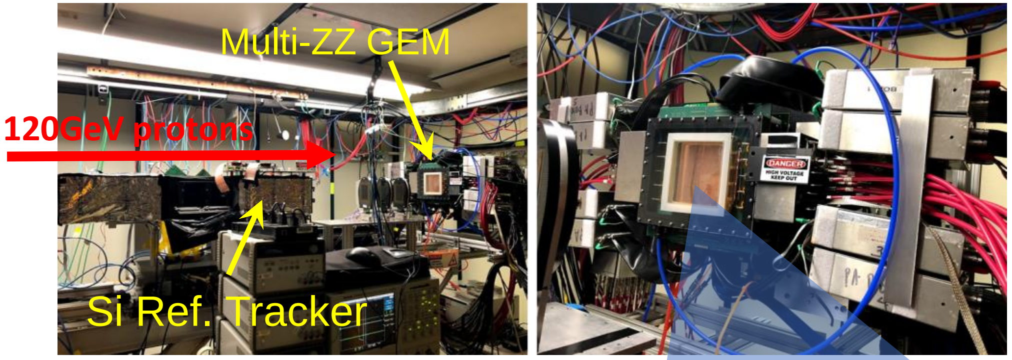


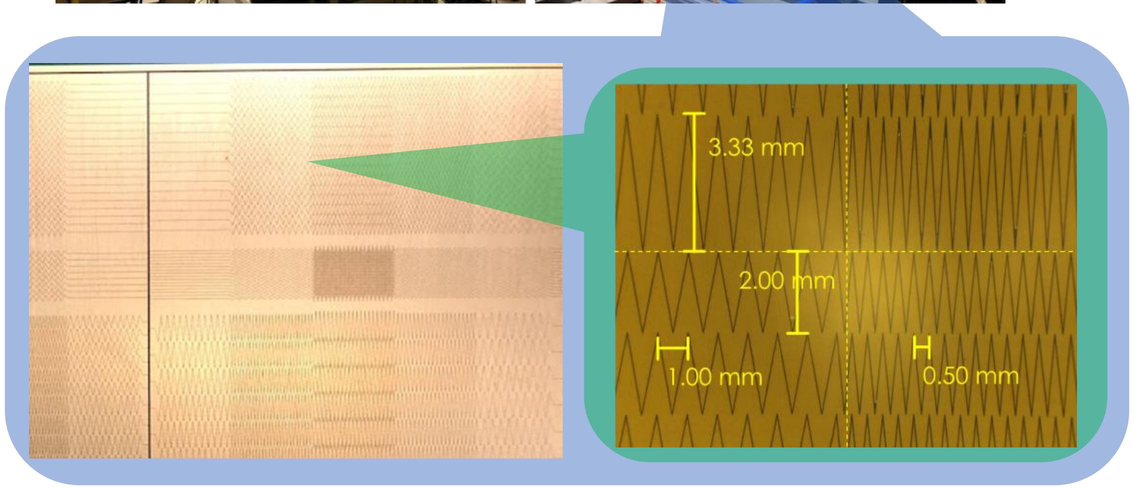
Fe55 spectrum w/ SAMPA



Progress @ BNL: ZZ Beam Test

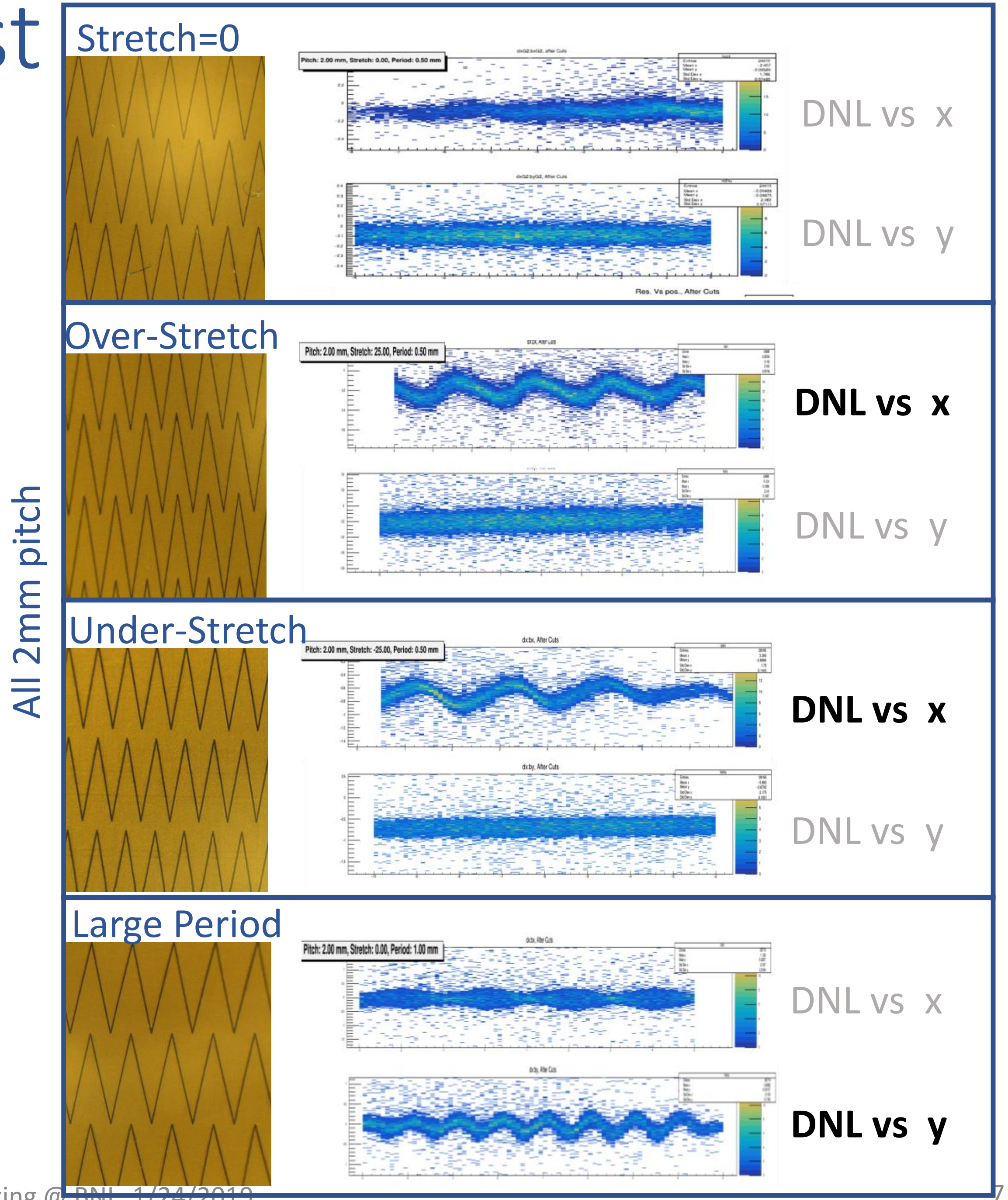
- ZZ R&D now funded by BNL LDRD, but mentioned here since it is a related effort





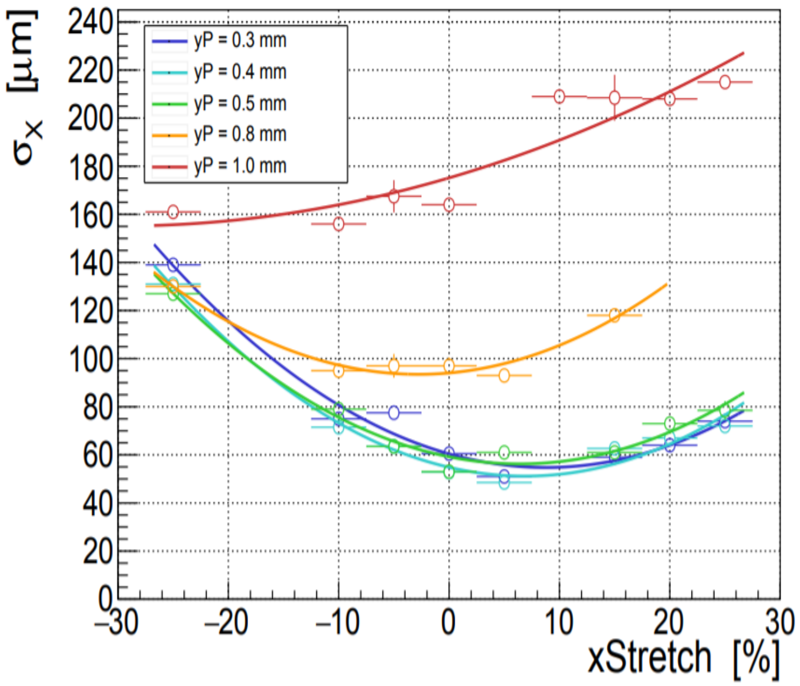
- “Multi-ZZ PCB: 10 x 10 array of 1cm x 1cm cells
  Laser-etched, gap fixed at ~24μm

- ZZ parameters varied broadly:
  Pitch: 0.4 - 3.33mm, Stretch: -25% - +25%, Period: 0.2 - 1mm



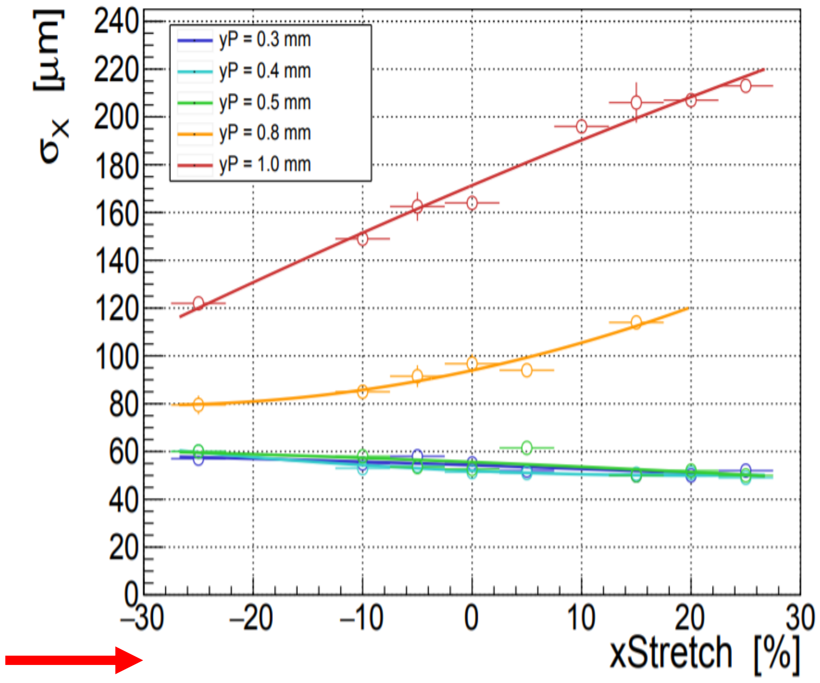
Progress @ BNL: ZZ Beam Test Results

Pitch = 2mm, No DNL correction



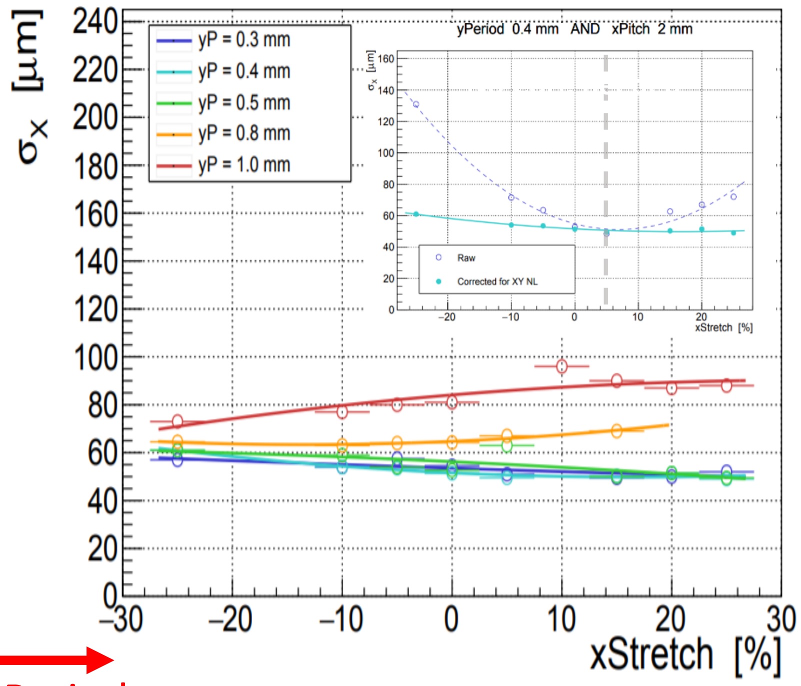
xStretch
Correction

Pitch = 2mm, DNL-x correction



yPeriod
Correction

Pitch = 2mm, DNL-xy correction

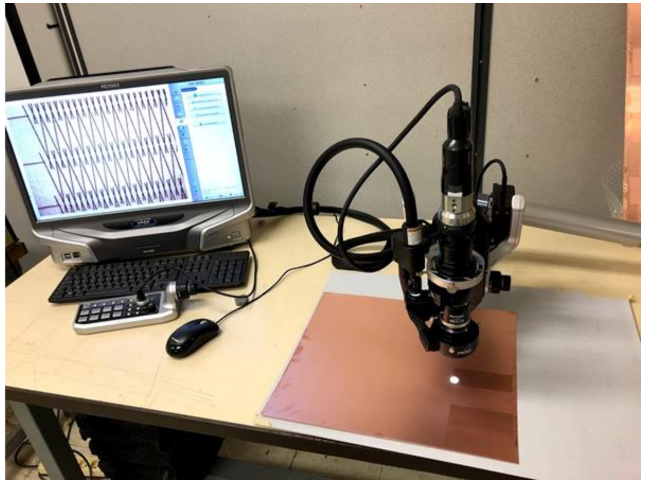


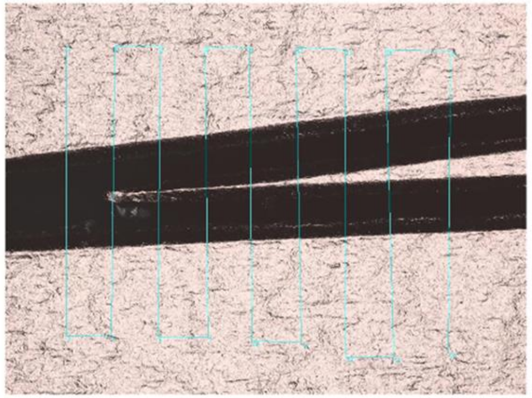
- Recover systematic offset in residuals using DNL-y correction followed by DNL-x correction
- Use centroid for correction, so process is limited by resolution of centroid itself
- At small periods, the impact of this parameter on performance becomes saturated
- **Inset plot identifies the point where no DNL correction is required and 50μm resolution is obtained for a pitch as large as 2mm!**

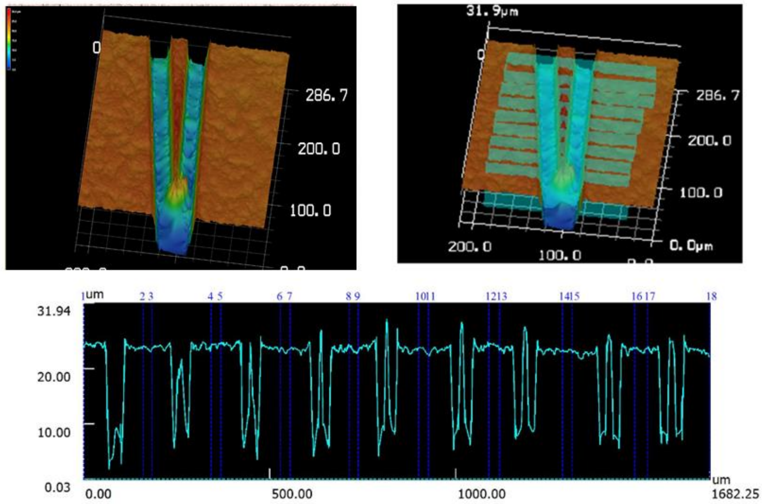
Progress @ BNL: Laser ablation

- Laser ablation is used in a novel way as the primary method to generate micropattern readout structure
- ~20mm wide trenches are able to be carved out of the copper+FR4 substrate, allowing the realization of unprecedented zigzag geometries
- **These new geometries are getting close to the ideal as suggested by simulation: ~40-50μm position resolution with NO differential non-linearity!!**
- Tuning the production parameters (eg, laser intensity, # of laser passes, machine instruction set) is informed by a rigorous QA routine
- Microscopic inspection of samples validates design specs and looks for damaging artifacts by examining the overall topology of the trenches

Laser ablation equipment at Elvia PCB manufacturing facility

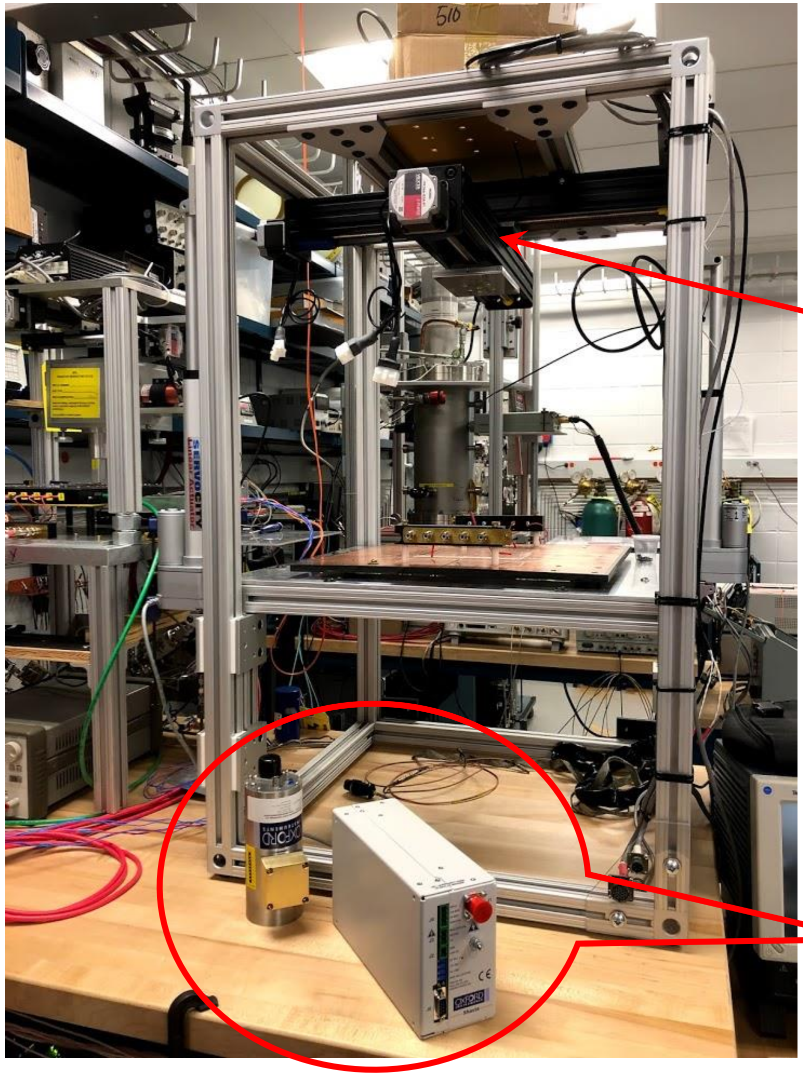






Progress @ BNL: High Intensity X-ray scanner

- High intensity, highly collimated x-ray beam (~20μm wide) for in-lab characterization of detectors under test
- Initially we were sold an x-ray source that was later determined to be inadequate for our needs (ie, equipped with a window which severely truncated the x-ray intensity spectrum)
- After much back and forth with manufacturer, we were able to exchange the source for one with a Be window, with virtually no cut-off
- We are now working to integrate the new source into the existing setup (XY-scanning stage and infrastructure already in place)



X-Y slides mounted to stand

New X-ray source & power supply

Progress @ BNL: Plans and Milestones

- January - March: Complete tracking software for the cosmic ray telescope, tune operating parameters, implement all the necessary calibrations

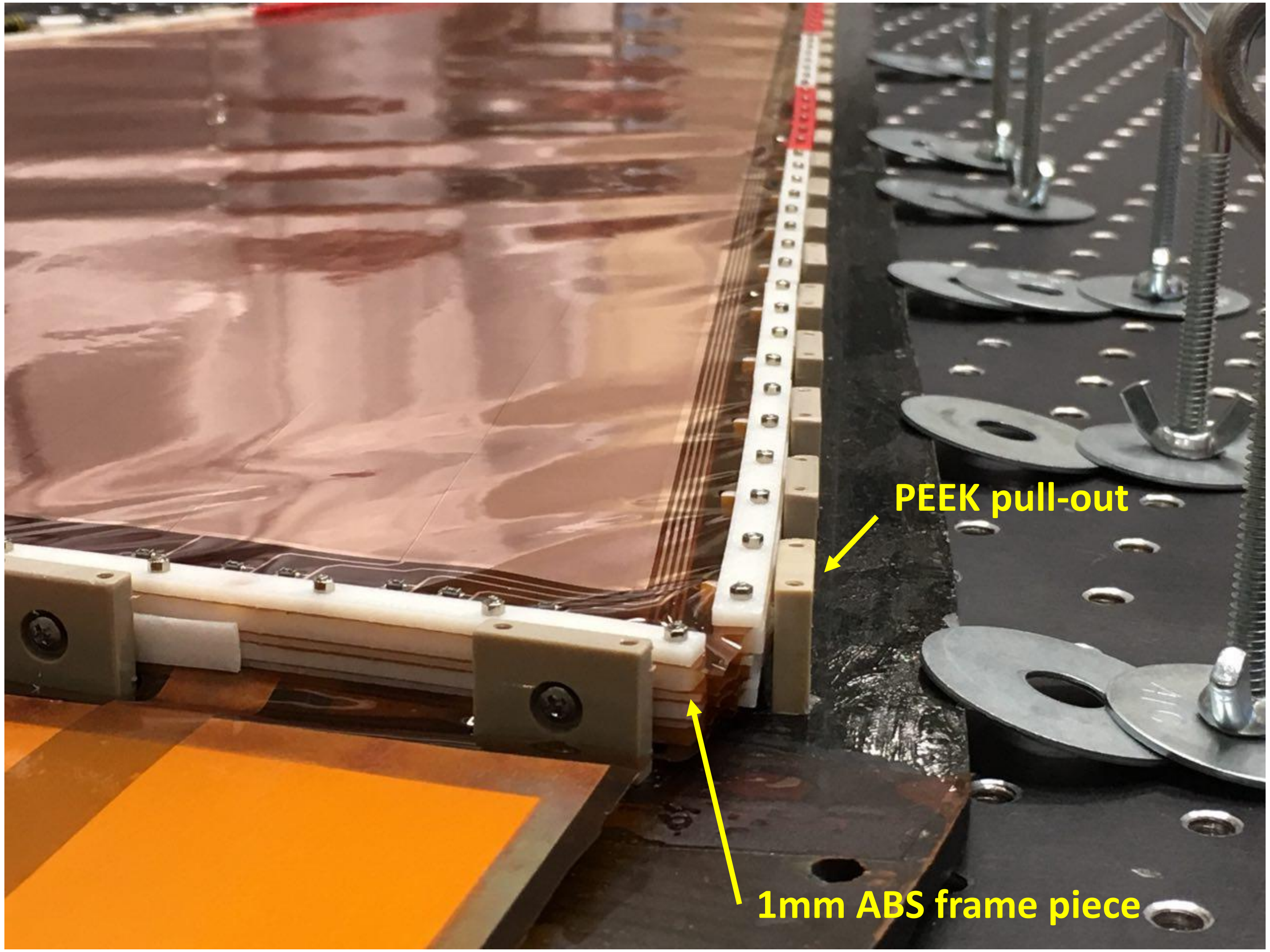
- January - June: Study track reconstruction in the TPC prototype using the cosmic ray telescope and attempt to get a first measure of the position resolution **in the lab**

- February - June: Read out the TPC with different electronics (ie, SAMPA and DREAM) and attempt to evaluate the performance for each case

- March - April: Study Micromegas and µRWELL with zigzag readout in a planar detector configuration (ie, short drift gap)

- March - June: Continue work on optimizing the design and production of zigzag readouts (LDRD) in parallel with the eRD6 R&D program

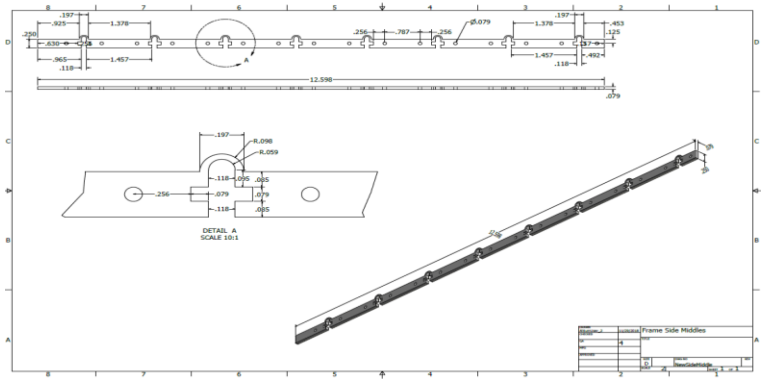
Progress @ FIT: Refurbishment of low-mass EIC Forward Tracker GEM detector prototype



Had observed shorts between GEM foils during FNAL beam test in summer 2018

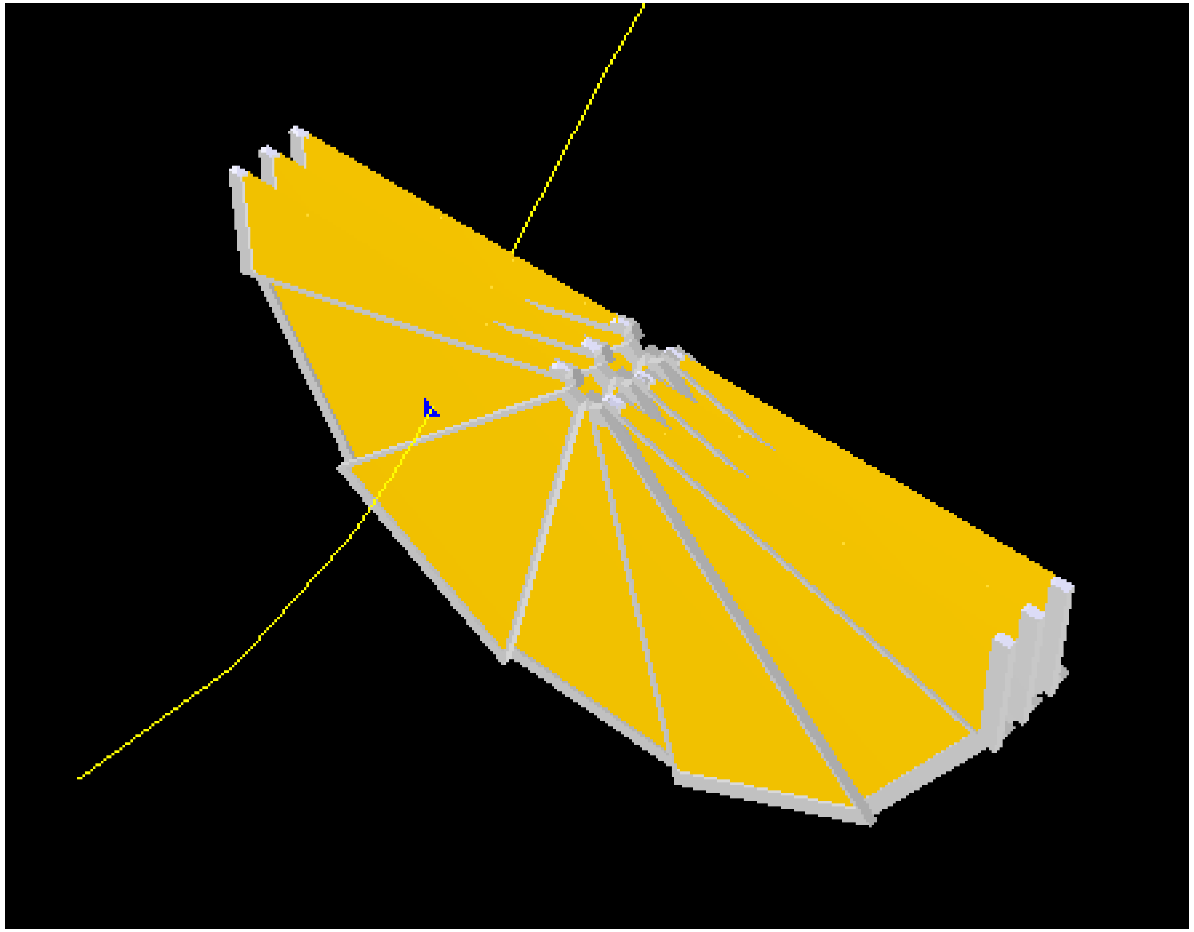
=> Refurbishing prototype detector:

- Replaced ABS pull-outs with stronger PEEK pull-outs
- Designing longer inner frame pieces that will also be made from PEEK

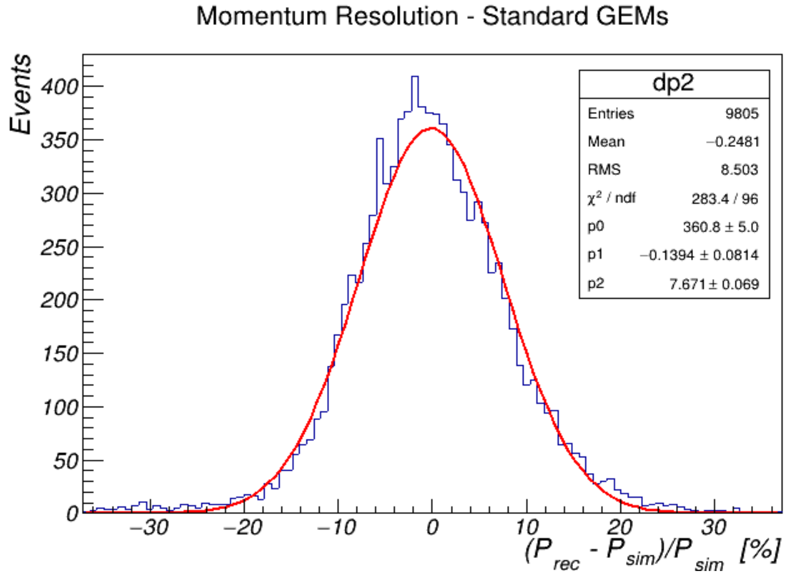


- Increase gap sizes from 3/1/2/1 mm to 3/2/2/2 mm

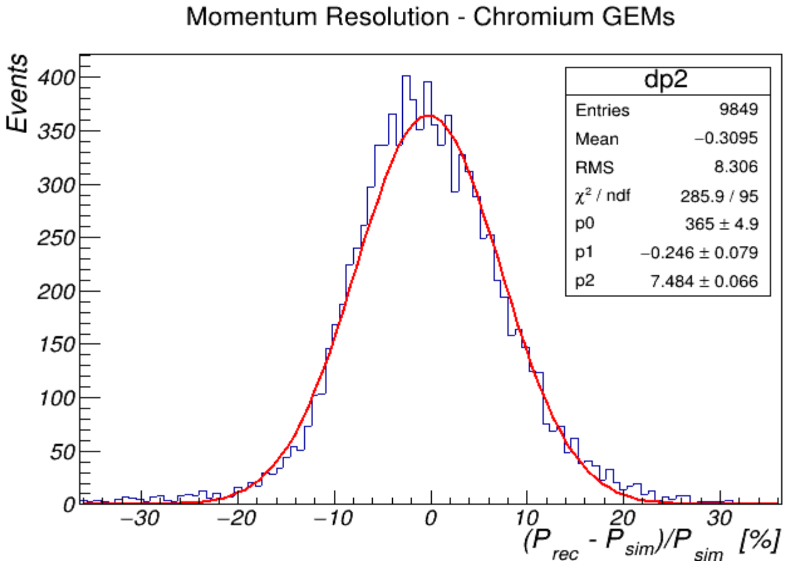
Progress @ FIT: Simulation of Cr-GEM forward tracker



EicRoot simulation of a 1 GeV/c electron track reconstructed stand-alone in three GEM stations in forward tracker region



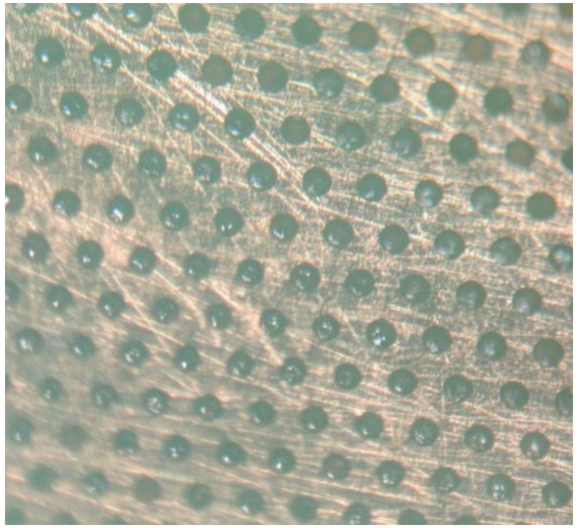
σ = 7.7%

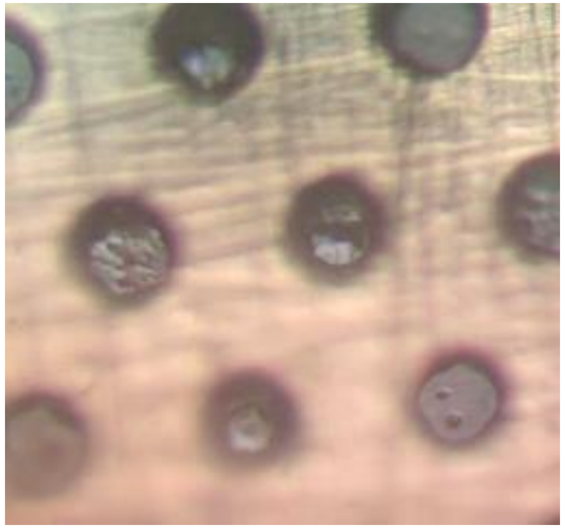


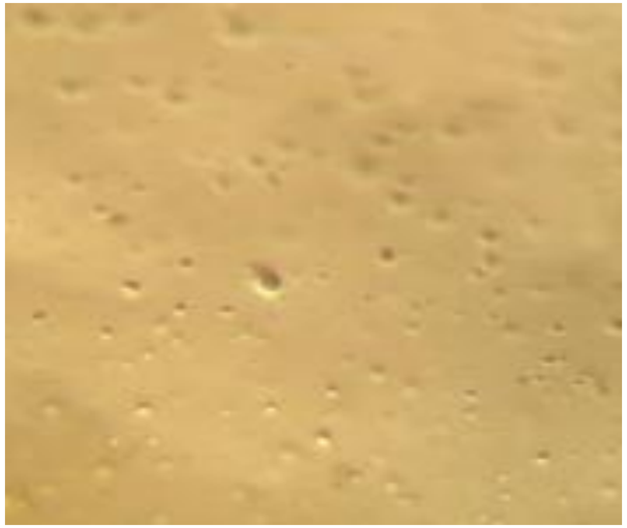
σ = 7.5%

Find only marginal improvement

Progress @ FIT: μRWELL prototype – basic studies

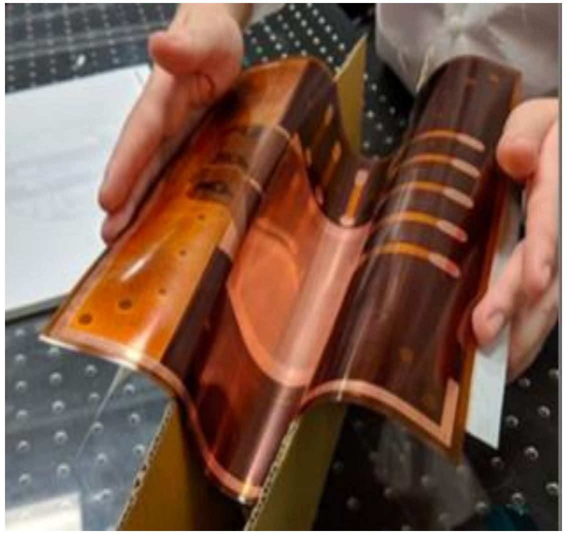




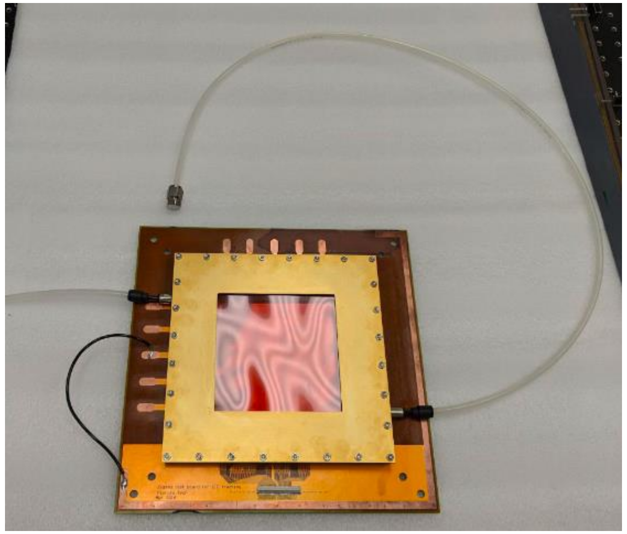


Observe non-uniformity of DLC layer at bottom of wells (bumps, divets)

convex bending



concave bending



assembled 10 × 10 cm planar μRWELL detector with zigzag r/o

μRWELL foil can be easily bent into cylindrical shape down to a radius of a few centimeter

No degradation of hole shape in bent foil observed under microscope

Progress @ FIT: Plans and Milestones

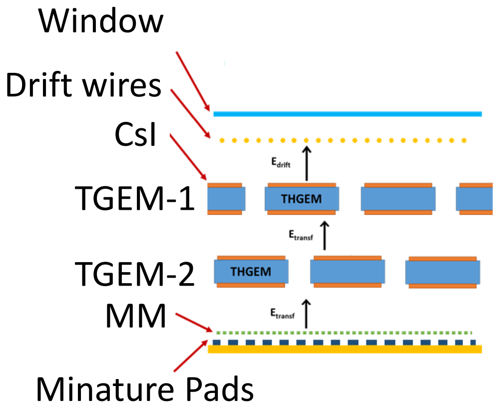
❑ Plans

- Forward Tracker Prototype:
  - Assemble the refurbished low-mass prototype and demonstrate that it can be operated
  - Characterize performance of the low-mass prototype with X-rays at Florida Tech
- EIC Simulations:
  - Extract hit residuals for tracks through the forward GEM chambers
  - Study how the reduction of material affects the spread of track position due to multiple scattering
  - Study precision of reconstructing track impact points on the RICH entrance window, i.e. seeds for ring reconstruction, with forward GEM trackers in front of and behind RICH
- RWELL detector:
  - Commission the 10×10 cm^2 μRWELL prototype with zigzag-strip readout
  - Characterize performance using X-rays.
  - Begin design for a small cylindrical RWELL detector together with UVa

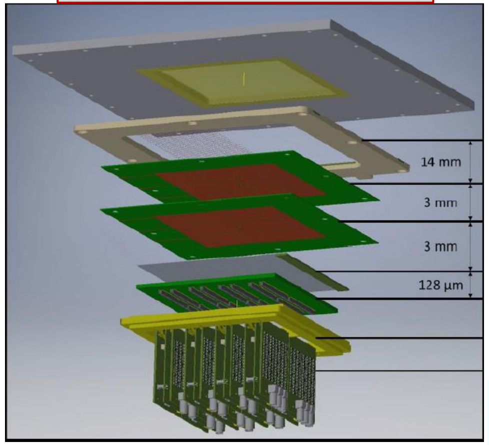
❑ Milestones

- Working low-mass prototype
- Working 10×10 cm^2 μRWELL prototype

Progress @ INFN: Photosensitive TGEM+Resistive MICROMEGAS prototype with miniaturized pads

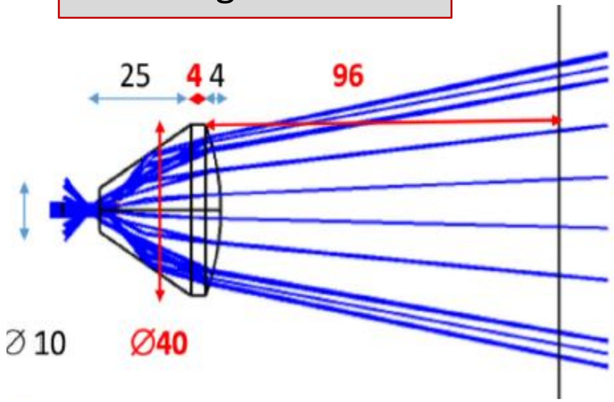


Detector prototype

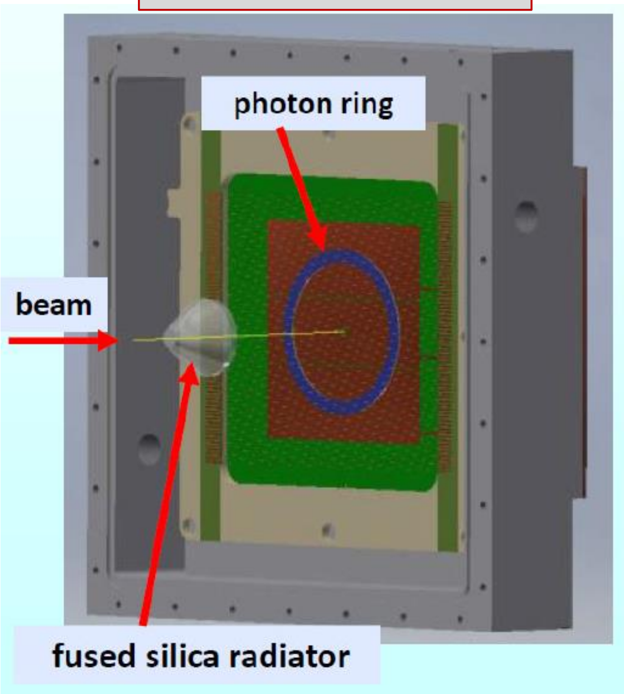


After completing the laboratory studies, the prototype equipped with a fused silica radiator was studied at a test-beam @ CERN *(Oct-Nov 2018)*

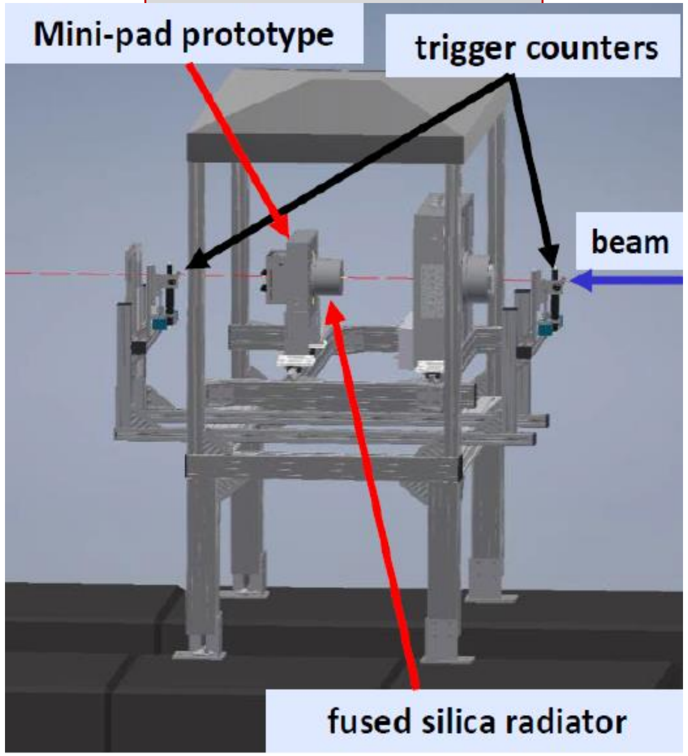
Fused silica radiator, the design



Fused silica radiator, the principle



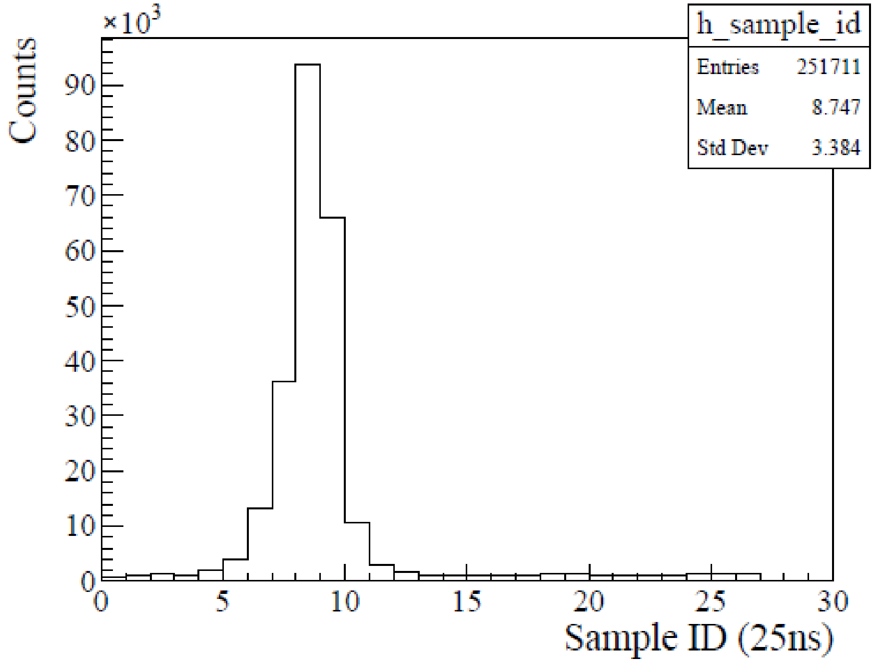
test-beam setup



Progress @ INFN: First hints from the test beam

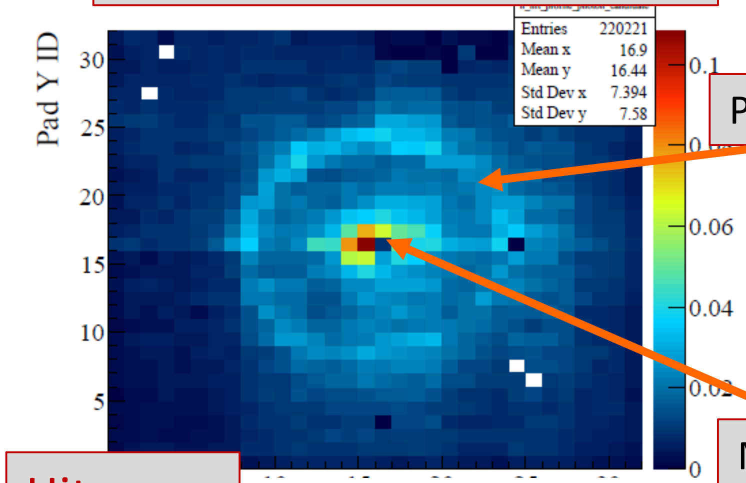
Time-development
of a single photon signal
(from on-line display)

Time distribution vs trigger time
of the Cherenkov photon signals



Progress @ INFN: First hints from the test beam

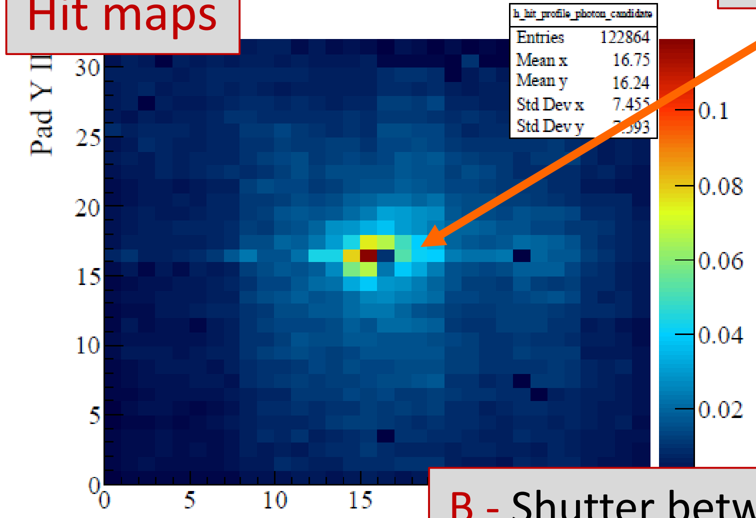
A - Shutter between detector and radiator OPEN



Photon ring

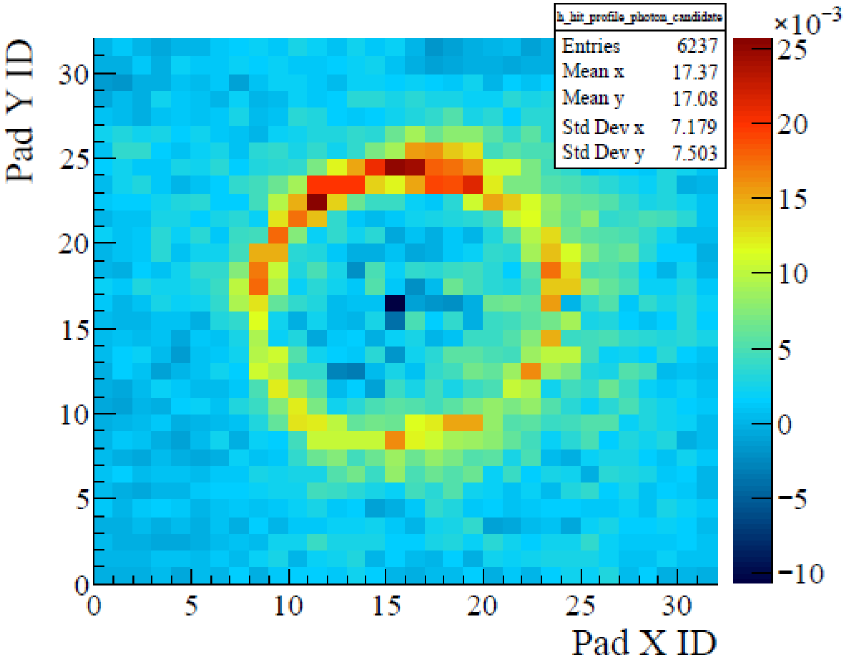
MIPs (beam)

Hit maps



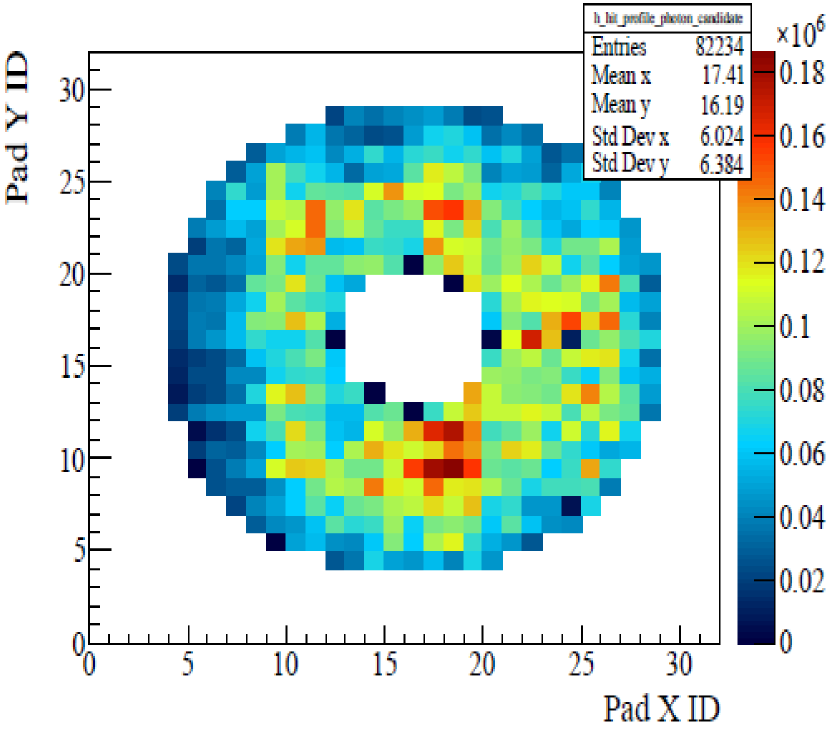
B - Shutter between detector and radiator CLOSED

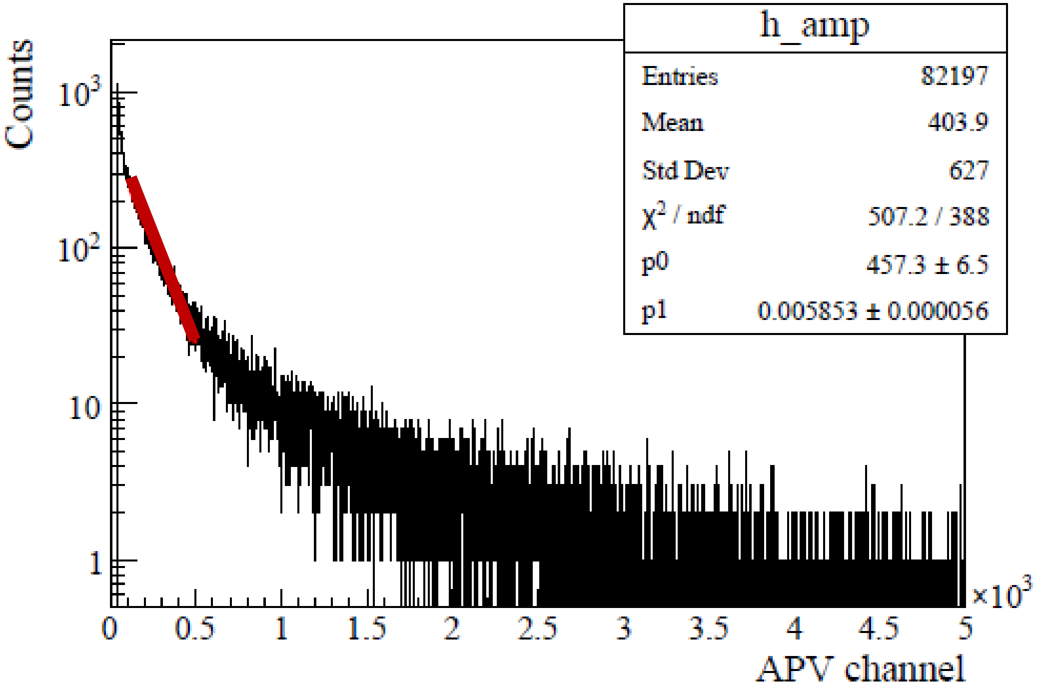
A – B (properly normalized): only the photon ring remains !



Progress @ INFN: First hints from the test beam

“ring region”





Signal amplitude in the ring region

Detector gain from the slope
of the exponential distribution (fitted):

Gain ~ 50 k !!!

Progress @ INFN: NanoDiamond (ND) photocathode

Initial studies of the compatibility of an innovative photocathode based on NanoDiamond (ND) particles with the operation in MPGD-based photon detectors

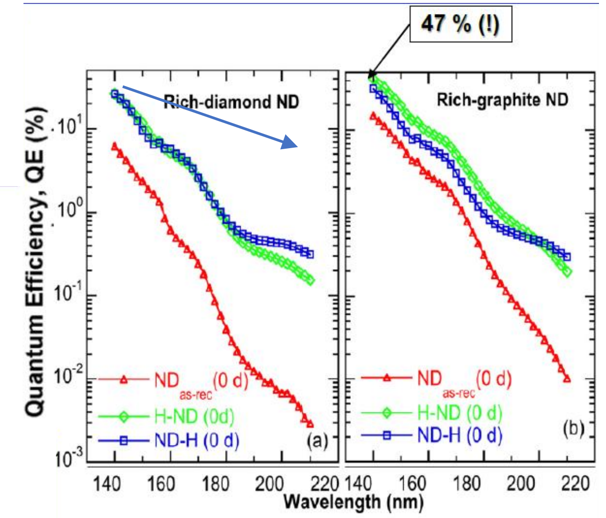
- Preliminary exercises reported in July2018

Unexpected feature:

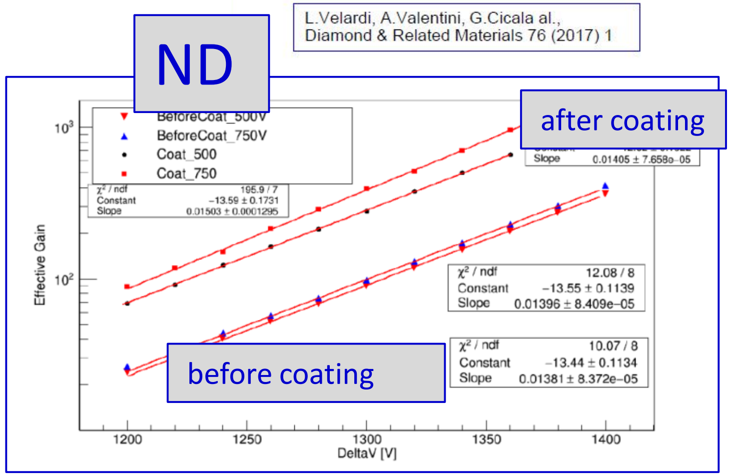
Gain increase in coated samples

- *A possible explanation emerging from repeated measurements:*
- The coating with the resistive material prevents charging-up phenomena in THGEMs
    - An observation of interest beyond this specific application

Reminder: the starting point



L.Velardi, A.Valentini, G.Cicala al., Diamond & Related Materials 76 (2017) 1



Progress @ INFN: Plans and Milestones

- Future (2019), <u>continuation</u> of the on-going R&D activities:

1. MICROMEGAS prototype with miniaturized pad-size
    - Completion of the analysis of the 2018 test-beam data
    - Construction of a second version of the prototype
    - Characterization of this second version by laboratory exercises

2. Coupling of innovative photocathode based on NanoDiamond (ND) particles to MPGD photon detectors
    - Production of a new set of small-size THGEM coated with ND and hydrogenated ND(HND)
    - Progress in understanding of the THGEM performance and features when coated with ND and HND by laboratory studies

- 2019 Longer Term MILESTONES:

    - September 2019: *The completion of the laboratory characterization of the second version of the photon detector with miniaturized pad-size.*

    - *September 2019: The completion of the studies to understand the performance of THGEMs with ND*

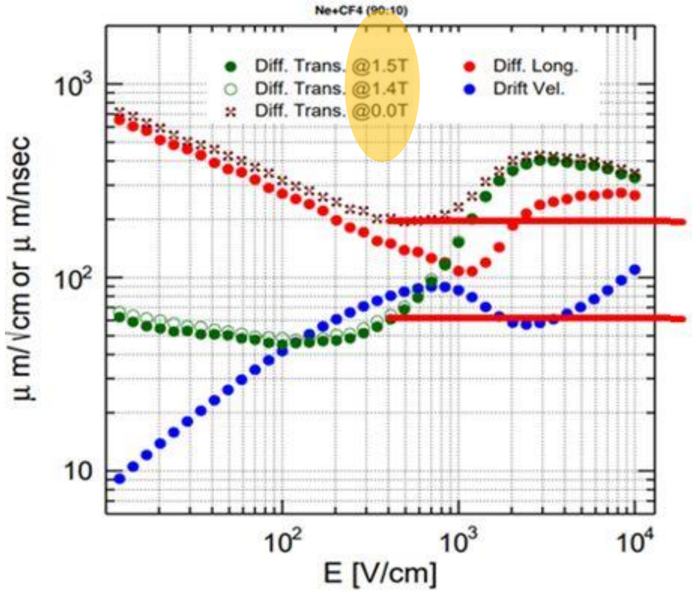
Progress @ SBU: Preparation for IBF Studies & Beam Test Results

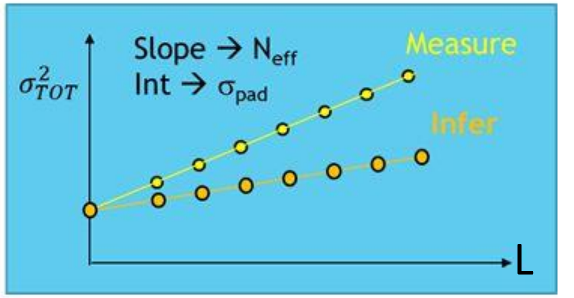
sPHENIX TPC → envisioned to serve as central tracker in day-1 EIC detector
Readout with three radial subdivisions: R1, R2, R3
TPC prototype at FTBF: Determination of working parameters with R2 module

- 120 GeV proton beam
- 4 drift-lengths
- B = 0 T, extrapolation to B = 1.4 T
- Compare to realistic GEANT4 simulation

$$\sigma^2_{total} = \sigma^2_{int} + \frac{D_T^2 L}{N_{eff}} + \cancel{\sigma^2_{sc}}$$

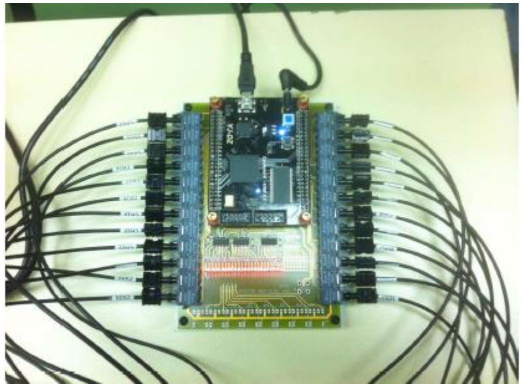
irrelevant due to small track density

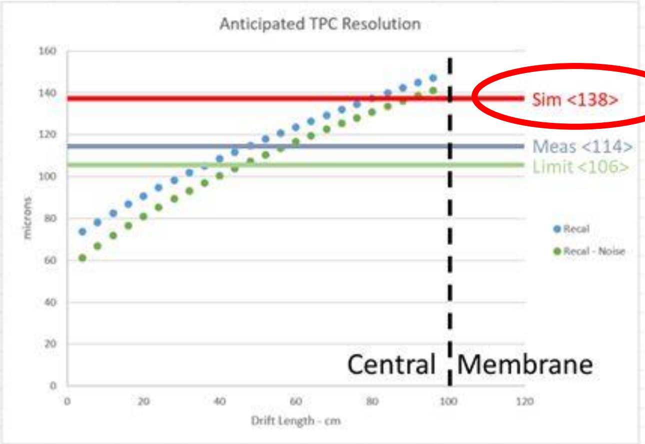


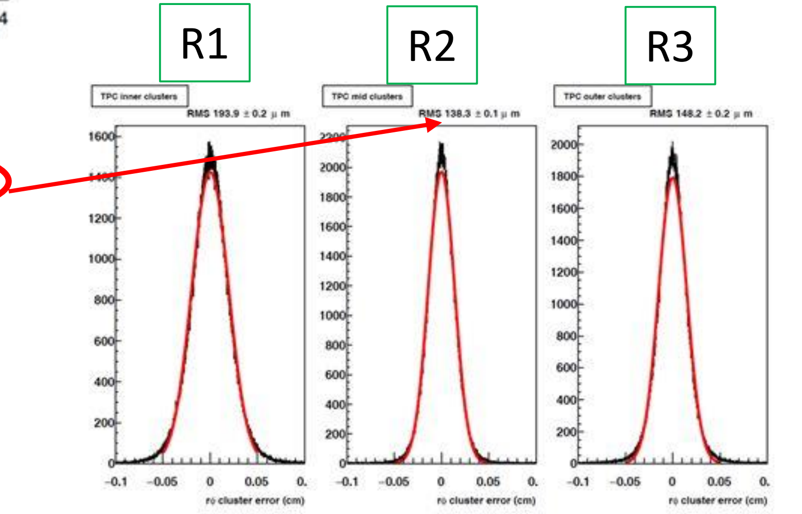


Preparing for IBF measurements with

- Picoammeter
- X-ray gun
- TPC prototype







Progress @ SBU: Evaluated TOM Procedures

Transformation optics procedures applied on directional permittivities/permeabilities → dispersion relation

$$\frac{\varepsilon_{x,x}}{\varepsilon_0\varepsilon_b} = \frac{\mu_{x,x}}{\mu_0} = \frac{g'(y)h'(z)}{f'(x)}$$

$$\frac{\varepsilon_{y,y}}{\varepsilon_0\varepsilon_b} = \frac{\mu_{y,y}}{\mu_0} = \frac{f'(x)h'(z)}{g'(y)}$$

$$\frac{\varepsilon_{z,z}}{\varepsilon_0\varepsilon_b} = \frac{\mu_{z,z}}{\mu_0} = \frac{f'(x)g'(y)}{h'(z)}$$

Dispersion relation:

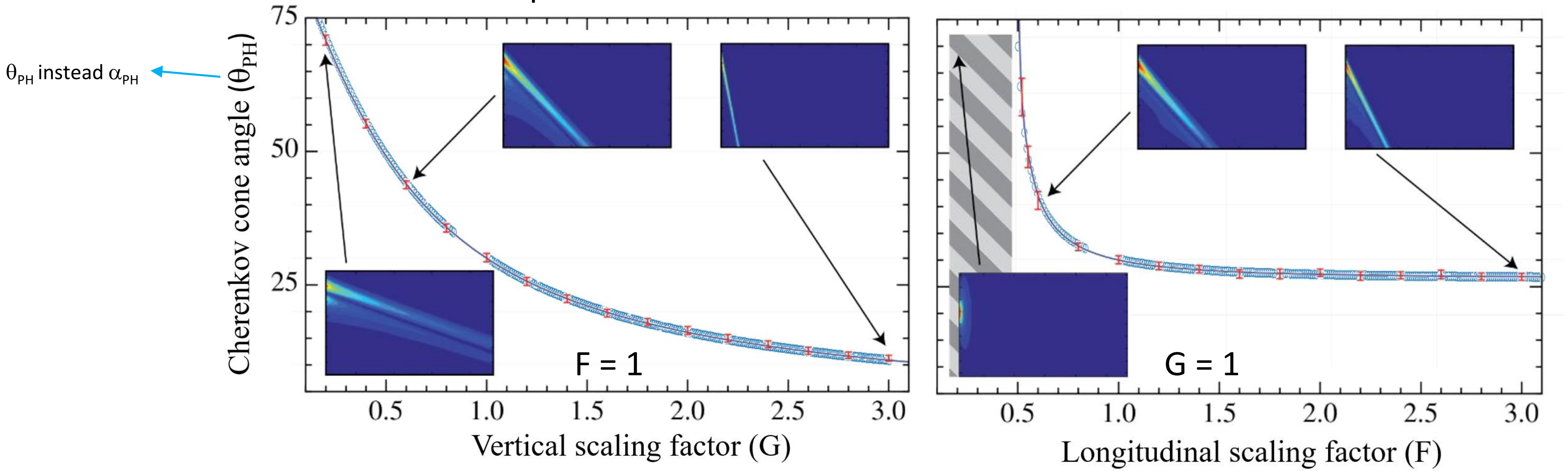
$$\frac{k_x^2}{f'^2(x)} + \frac{k_y^2}{g'^2(y)} + \frac{k_z^2}{h'^2(z)} = \epsilon_b \frac{\omega^2}{c^2}$$

and

$$f'(x) = F\ (= \tfrac{\partial x}{\partial x'}),\ g'(y) = G\ (= \tfrac{\partial y}{\partial y'}),\ h'(z) = H\ (= \tfrac{\partial z}{\partial z'})$$

$$\tan(\alpha_{PH}) = \frac{k_y}{k_x} = \frac{G}{F}\frac{\sqrt{F^2\epsilon_b\omega^2/c^2 - k_x^2}}{k_x} = \frac{G}{F}\tan(\theta_{Ch,n_b})$$

Blue open circles overlaid on full-wave numerical simulations



Started COMSOL simulation effort

2nd attempt to invite Prof. Capasso

Progress @ SBU: Mirror coating project

- Continuing installation effort
- Equipment installation into evaporator almost complete
- Connecting to external equipment under way
- Start-up expected at end of 1st quarter '19

Progress @ SBU: Plans and Milestones

- January – March ’19

  IBF studies (Abstract to MPGD2019 submitted)

- February – April ’19

  Simulation of meta-materials

- January – April ’19

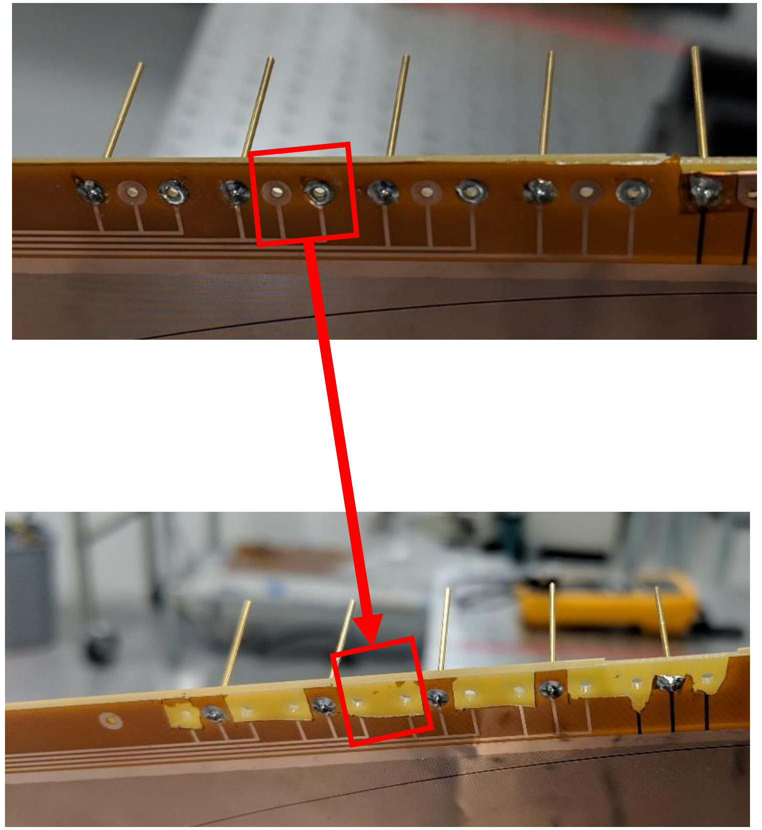
  Finalizing installation of mirror coating equipment

- April – May ’19

  Commissioning evaporator

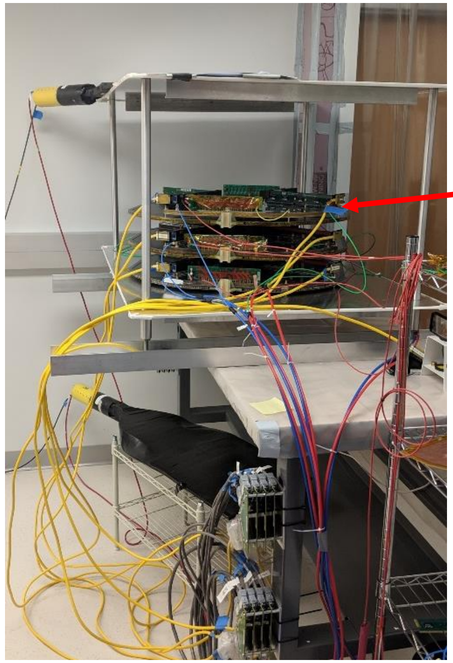
Progress @ TU: Commercial Triple GEM Detector

- **Goal** is to build and characterize triple-GEM detectors using **commercial foils** (Tech-Etch) and **Kapton spacer rings** rather than G10 spacer strips.
- Identified and corrected the shorting issue with first two triple-GEM detectors which rendered them useless.
- **Third triple-GEM detector** implemented shorting fix by removing unused HV pads.
- Foils have been stretched and glued to their respective frames for the **fourth triple-GEM detector.**



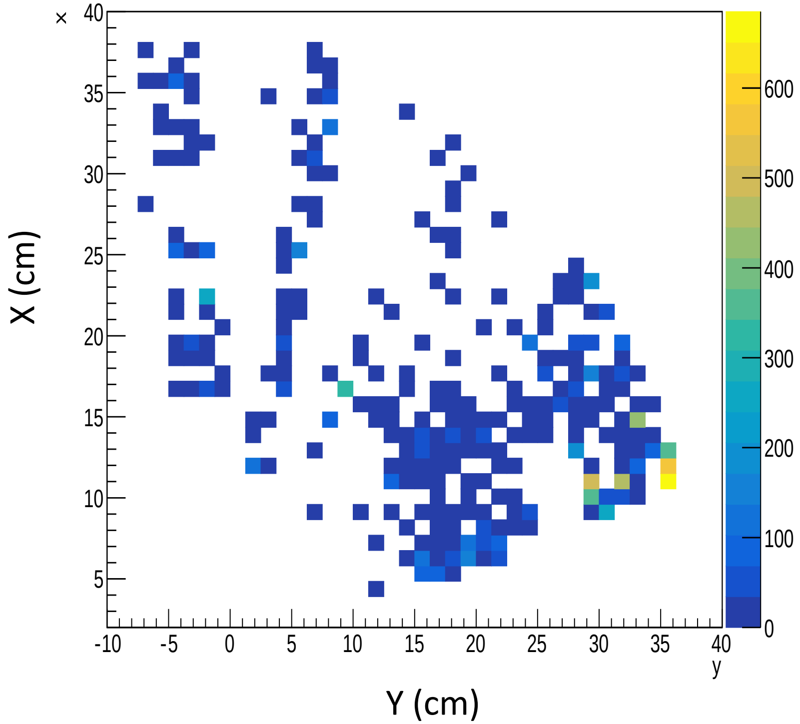
Progress @ TU: Commercial Triple GEM Detector

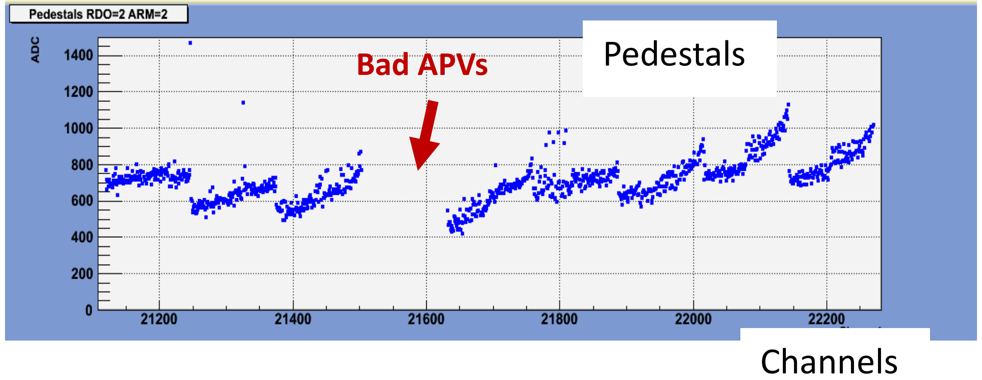
- We see signal from cosmics with the third triple-GEM detector, but some issues too → currently investigating
  - 2 APV chips are bad
  - Electronic mapping issues
- Characterization (cosmic/ ^{55}Fe) of third and fourth triple-GEM detector will complete the eRD3 carry over R&D



EIC Prototype

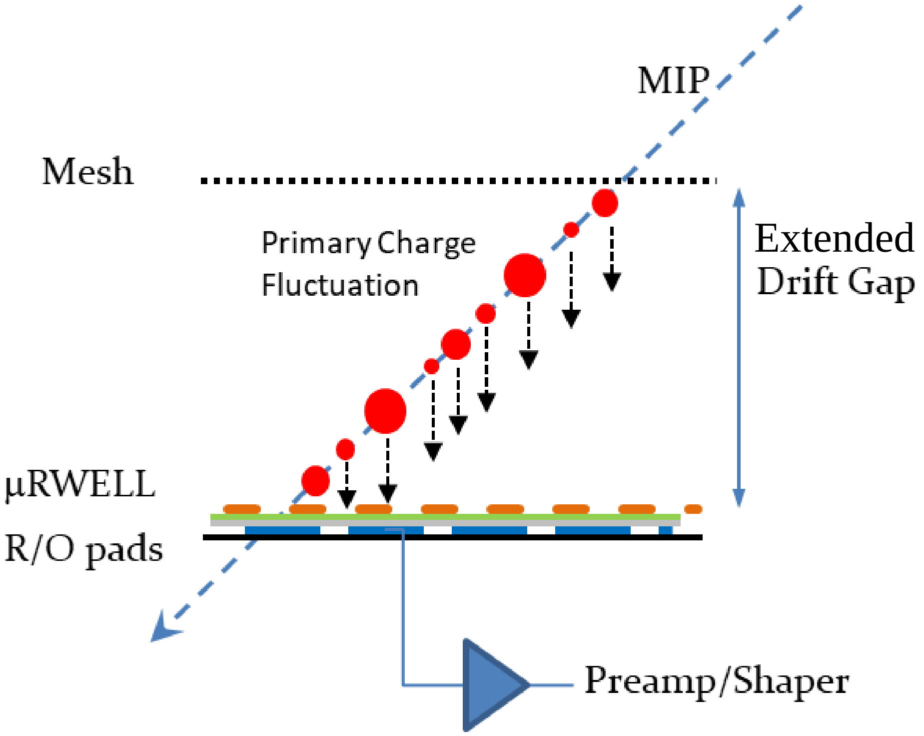
EIC Prototype 3: Initial cosmic signal





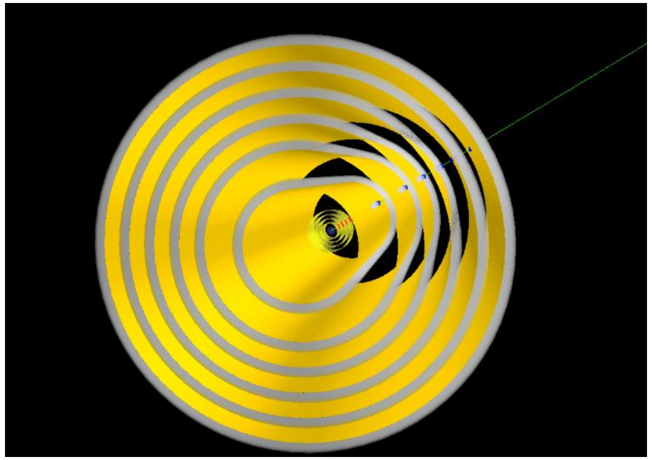
Progress @ TU: μRwell μTPC Barrel Simulation

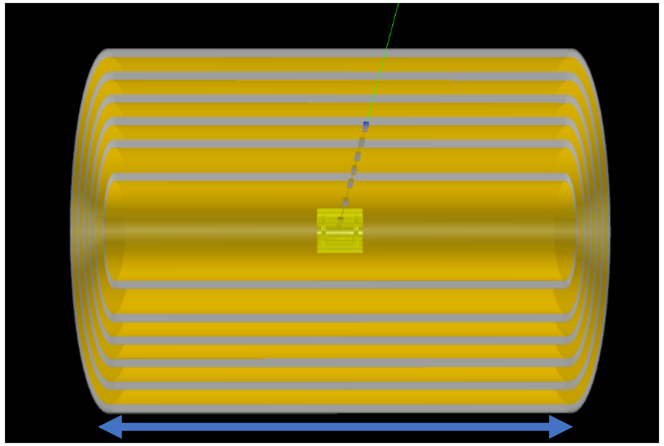
- **Goal** is to simulate use of $\boldsymbol{\mu RWell}$ operating in μTPC mode in the central rapidity region to study performance
  - May be useful option at a second EIC IR where TPC technology is not wanted.
  - $\mu RWell$ can also be used with silicon detectors to provide fast readout to distinguish particle bunches.



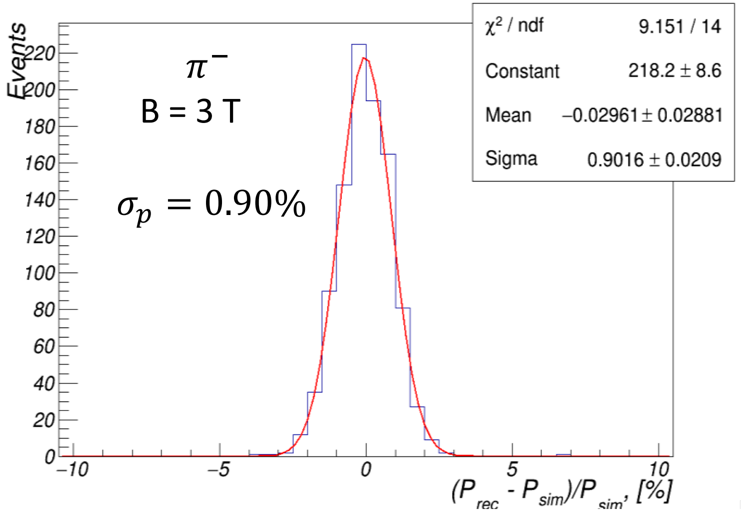
Progress @ TU: μRwell μTPC Barrel Simulation

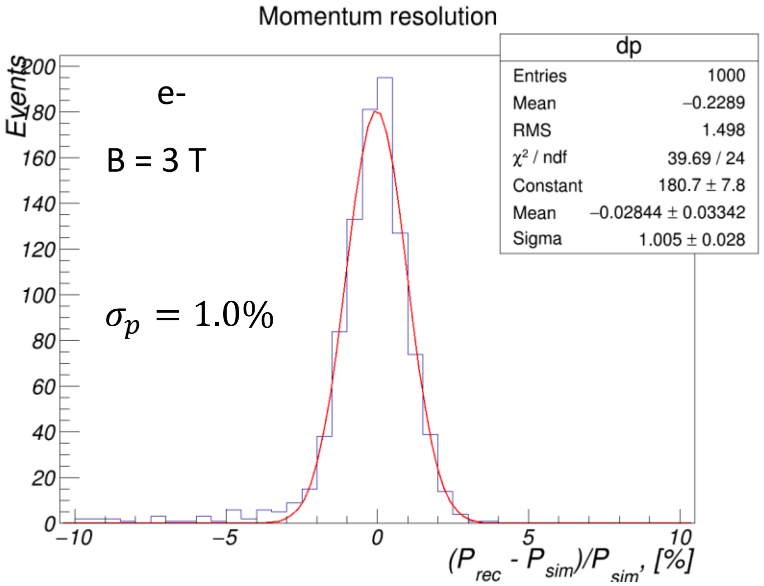
- Machinery to simulate low-mass $\mu RWell$ μTPC barrel has been setup within EICRoot framework.
- Consists of 6 barrel layers (r = 225 mm – 775 mm) with each layer having
  - $\chi_{o,foil} = 0.172\%$ (detector and readout foil)
  - $\chi_{o,gas} = 4\ cm$ (ArCO2:70,30 – defined in EICRoot)
- To simulate the multiple hit points within a TPC, each barrel layer contains 10 4 mm sensitive layers with 50 μm resolution in ϕ and z.
- Simulation also consists of 4 silicon detectors with 20 μm resolution.





2m





Progress @ TU: Plans and Milestones

❑ Plans

- Commercial Triple-GEM Detectors
  - Test remaining APV cards (**March**)
  - Complete electronic mapping (**March**)
  - Complete cosmic and ^{55}Fe detector characterizations → completes eRD3 carry over R&D (**end of year**)
- $\mu RWell\ \mu TPC$ barrel simulation
  - Implement more realistic hit point resolutions in to barrel μTPC based on radial TPCs and eRD6 μTPC prototypes, e.g. mini-drift detector (**April**).
  - Simulate track residuals and charge discrimination (**June**).

Progress @ UVA: Large Area Triple-GEM with U-V r/o

Three novel ideas tested with this large prototype

❖ **Low Mass Detector:**

⇨ GEMs, cathode & U-V r/o are all Kapton foils

⇨ No rigid PCB or honeycomb support in active area

⇨ Entrance and exit window ⇨ uniform gap b/w layers

⇨ **Detector radiation length = 0.41%**

❖ **Low Cost Support Frames:**

⇨ Four inner frames with spacers for GEMs & drift foils

⇨ by RESARM (Belgium) ⇨ higher cost

⇨ Four outer frames for gas window & top frames

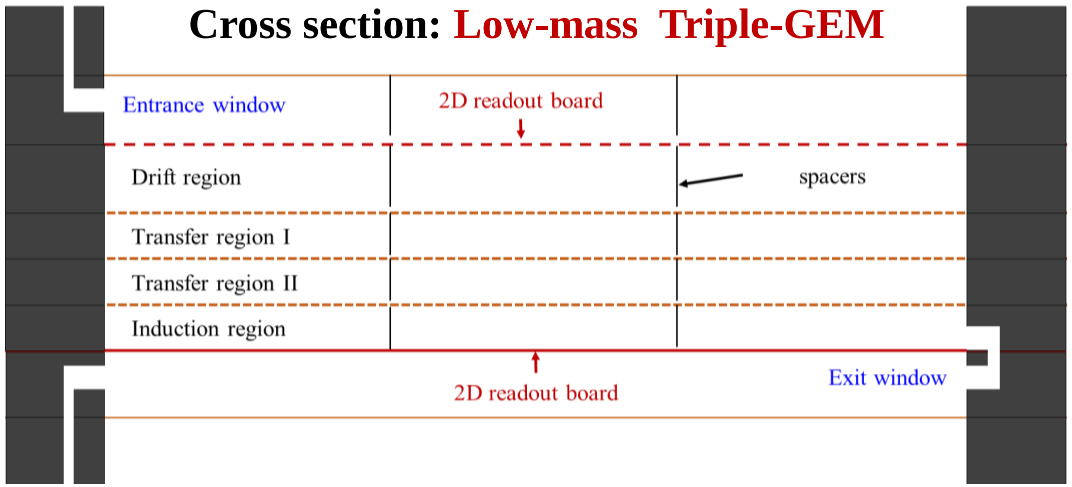
⇨ locally produced at lower cost standard G10

⇨ **Saving: ~ 30% in overall production cost ($)**

❖ **U-V readout with double-sided zebra connection:**

⇨ All e- channels read out at the outer radius ⇨ No FE cards on the back or side of the detector

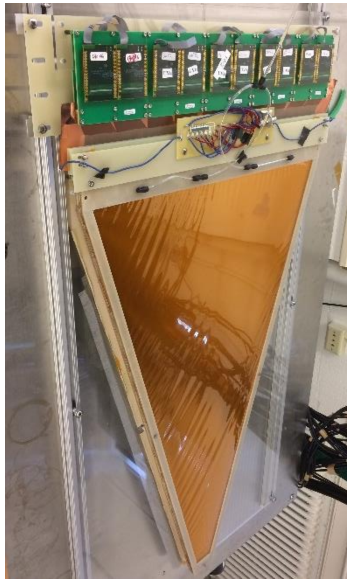
⇨ No vias necessary on the readout foil ⇨ minimize Cu layer thickness for U and V strips



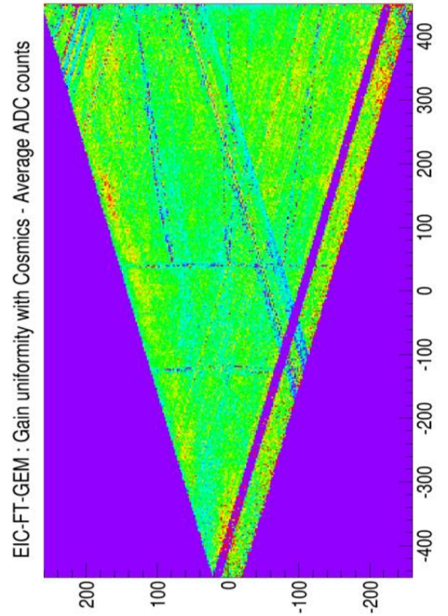
Common GEM Foil

U-V strips readout foil

Large GEM Prototype



Response uniformity

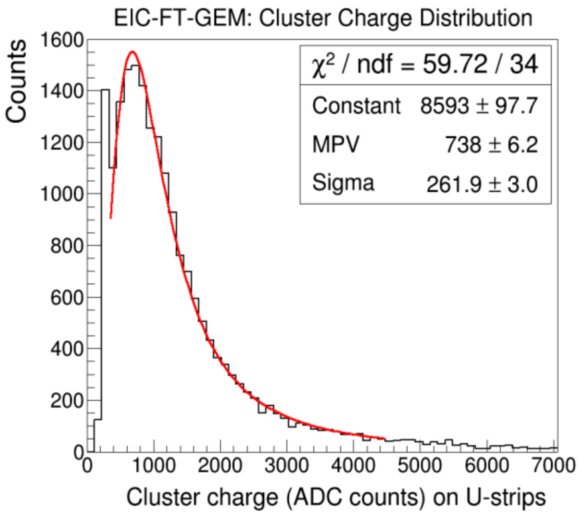


Progress @ UVA: Beam test results

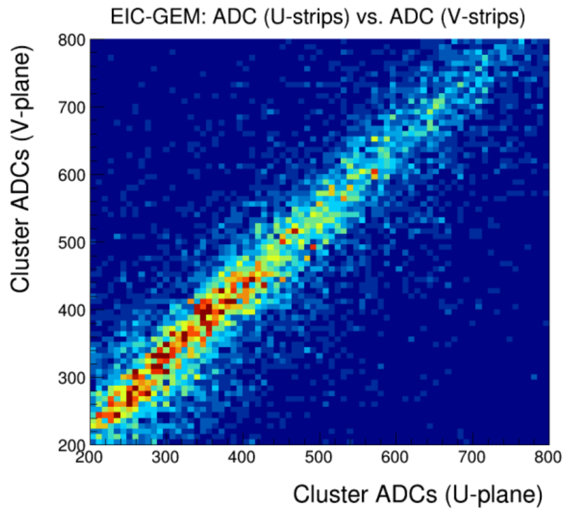
Characterization of the prototype in test beam at FNAL

- **FTBF 120 GeV primary proton beam**
  - ⇨ APV25-based SRS Readout at 0.5 kHz trigger rate
  - ⇨ Very good overall performance of the prototype
- **Performance of the U-V strip readout:**
  - ⇨ ADC distribution ⇨ Characterization of zebra connection
  - ⇨ Excellent charge sharing between U and V strip layers
  - ⇨ Spatial resolution in x & y direction ⇨ close to expected performances

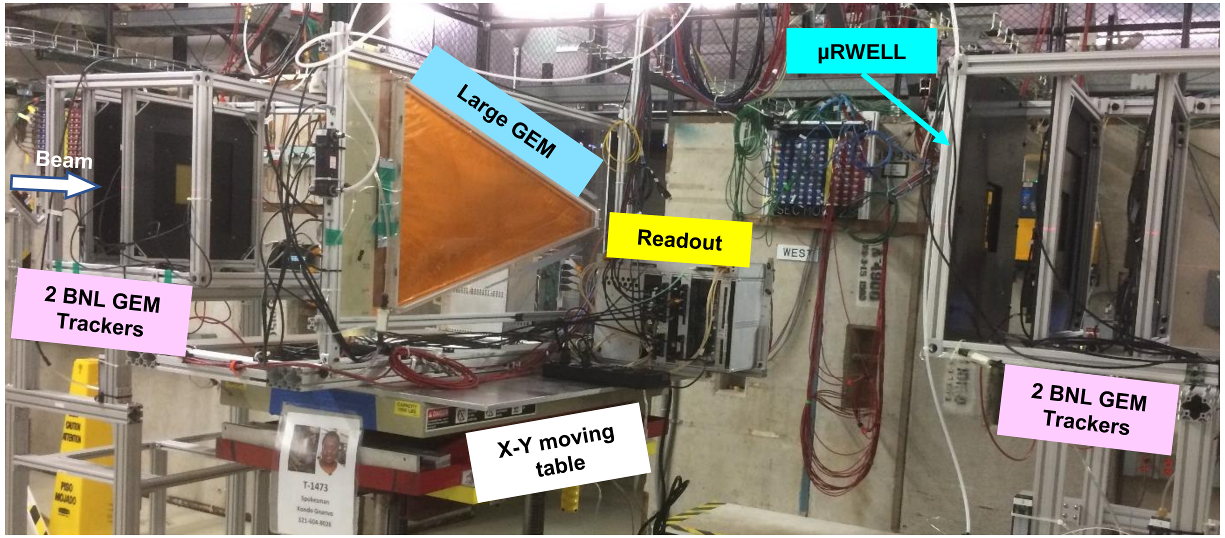
ADC Distribution on U-strips



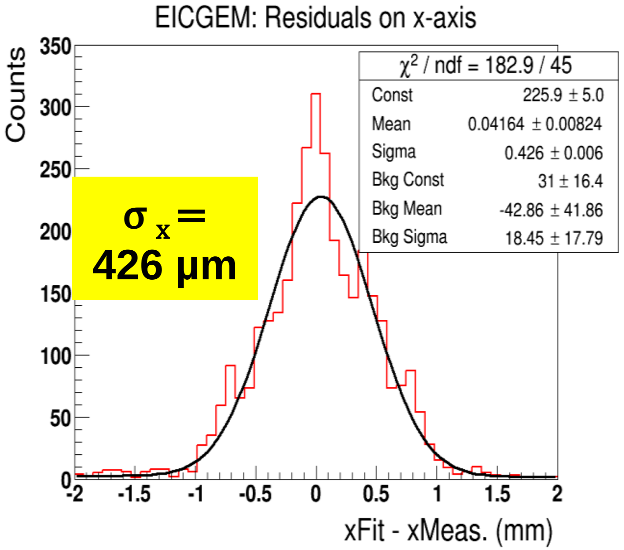
U-V strips charge sharing

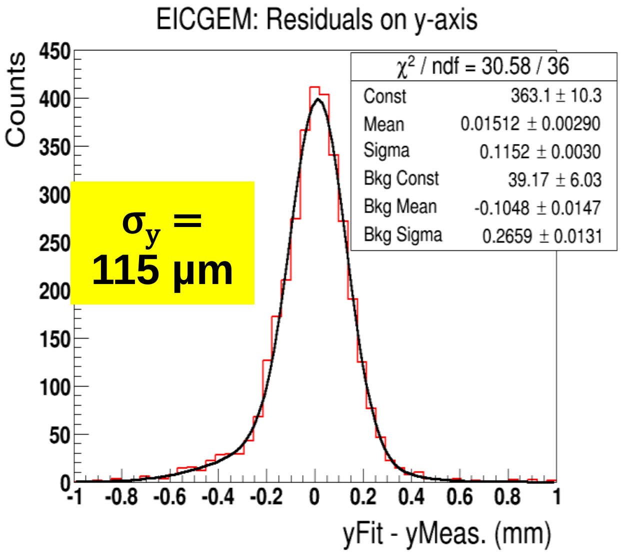


Large GEM Setup in MT6.2b Area at the FTBF (June-July 2018)



Spatial resolution of the detector with U-V strip readout

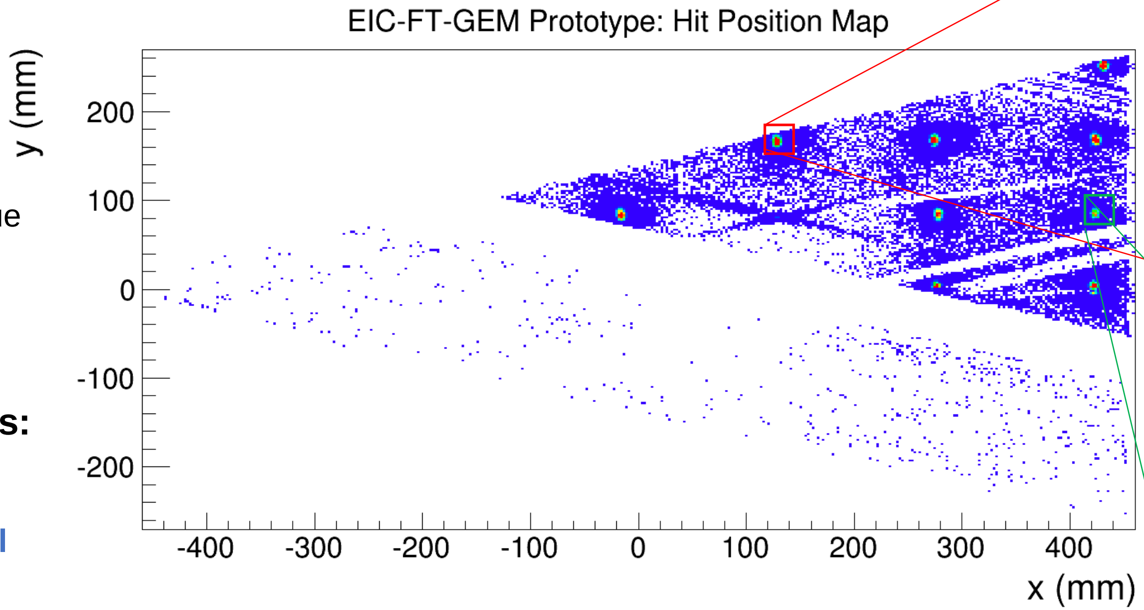


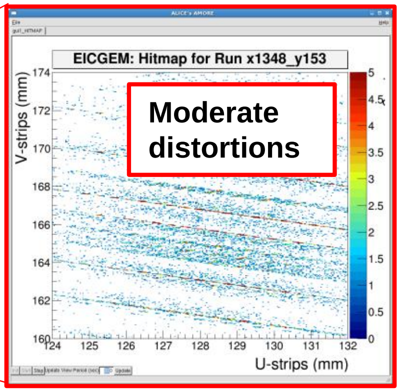


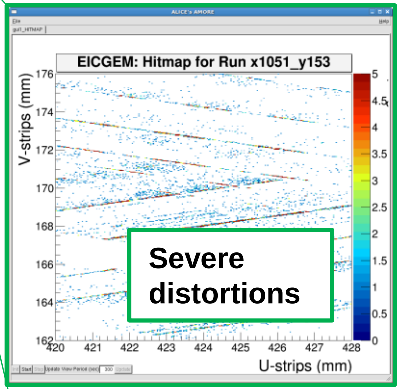
Progress @ UVA: Production Quality Issues

Production quality issues with the U-V readout

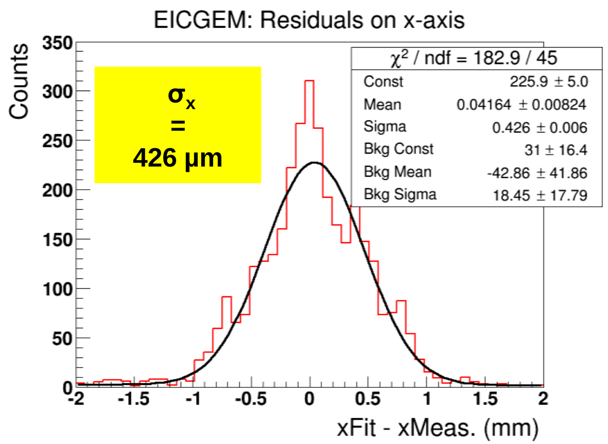
- **Strange pattern in the reconstructed positions**
  - ⇨ We normally expected uniform distribution of the position
- **Cause of the problem still under investigation**
  - ⇨ Looks like a lot of strips are shorted, but could also be an issue with the zebra connection or the quality of the zebra strips
  - ⇨ Pattern effect more pronounced in some area than other
- **Degradation of the spatial resolutions performances:**
  - ⇨ More pronounced where the distortions are severe
  - ⇨ **But it is a production quality issue and not a fundamental issue with the U-V readout with double zebra connection**

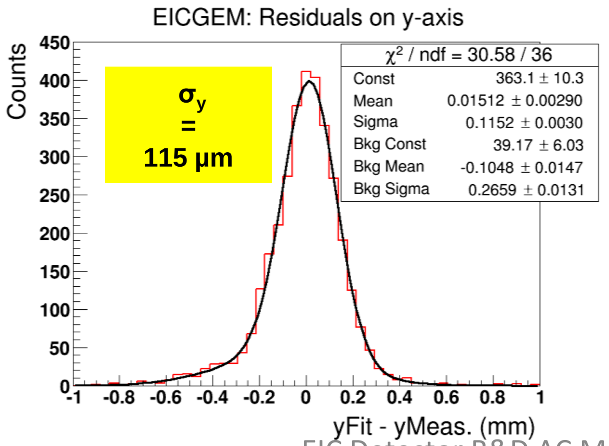




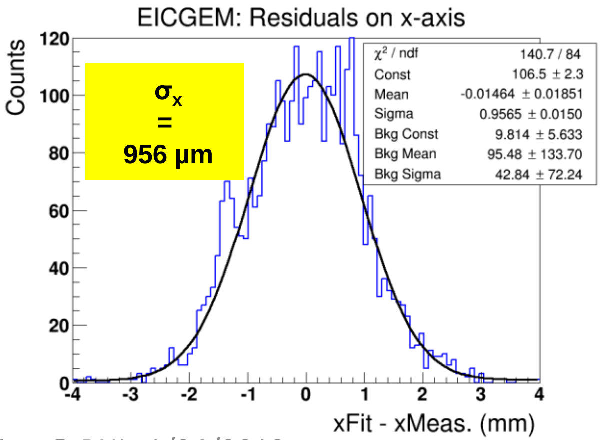


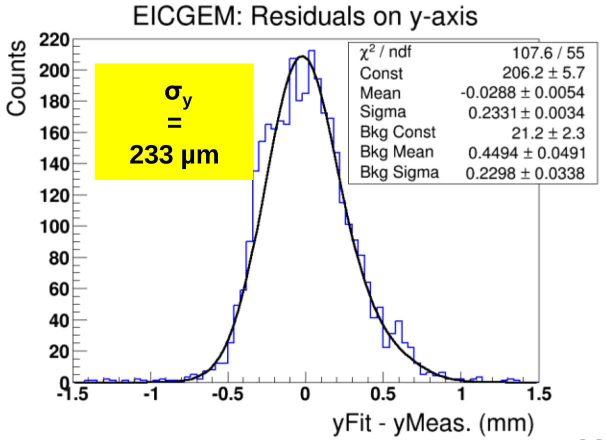
Spatial resolution: moderate distortion area





Spatial resolution: severe distortion area



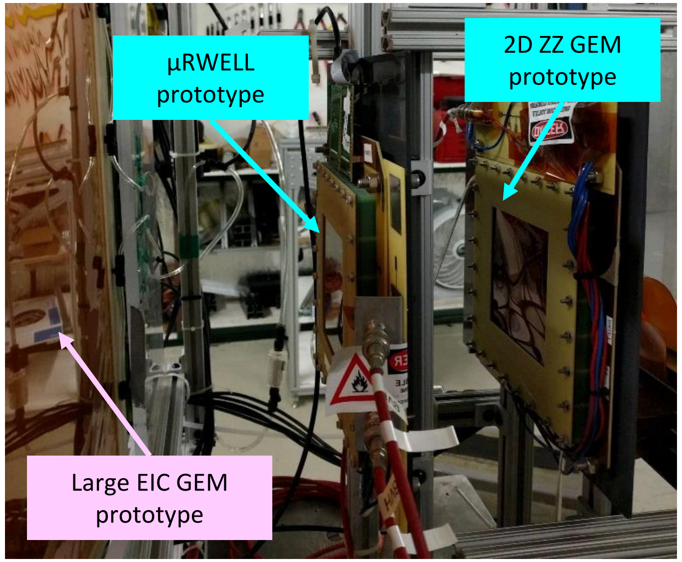


Progress @ UVA: Small µRWELL Prototype w/ 2D r/o

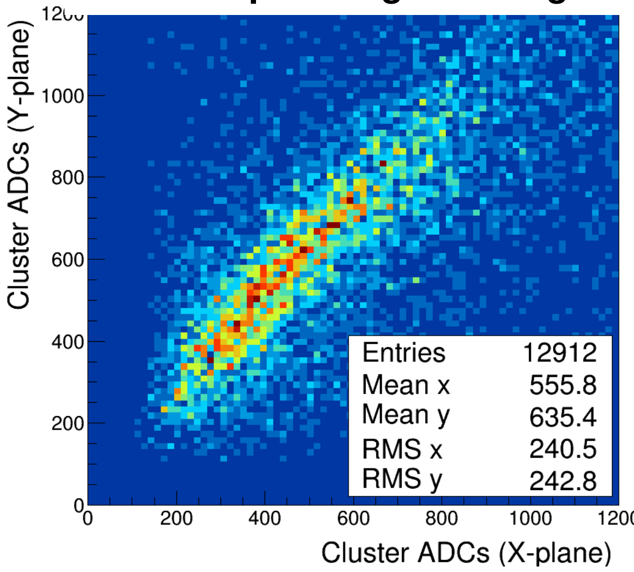
Characteristics of the 10 × 10 cm^2 µRWELL prototype

- **2D (X-Y) strips readout**
  - ⇨ Strips: same pitch (400 µm) as for COMPASS 2D readout
  - ⇨ **X vs. Y charge sharing via capacitive coupling**
  - ⇨ X and Y strip layers are separate by 50 µm glass epoxy layer
- **µRWELL prototype in FNAL test beam**
  - ⇨ Operated with standard Ar-CO2 (70/30)
  - ⇨ Charge sharing correlation between x and y strips
  - ⇨ Width of track fit residual: 50 µm in x and 43 µm in y
    - ⇨ **Expect even better resolution after track fit correction**

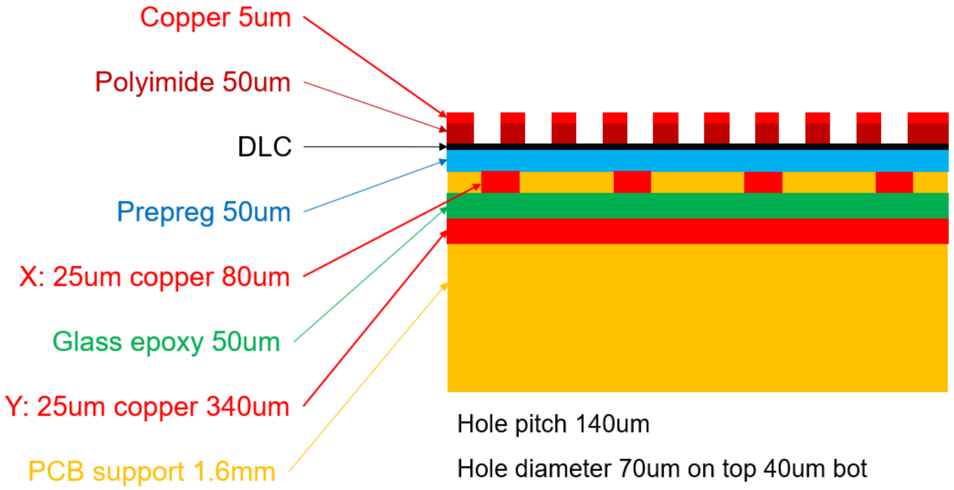
µRWELL at FTBF beam test 2018)



X-Y strips charge sharing



Cross section of µRWELL X-Y readout

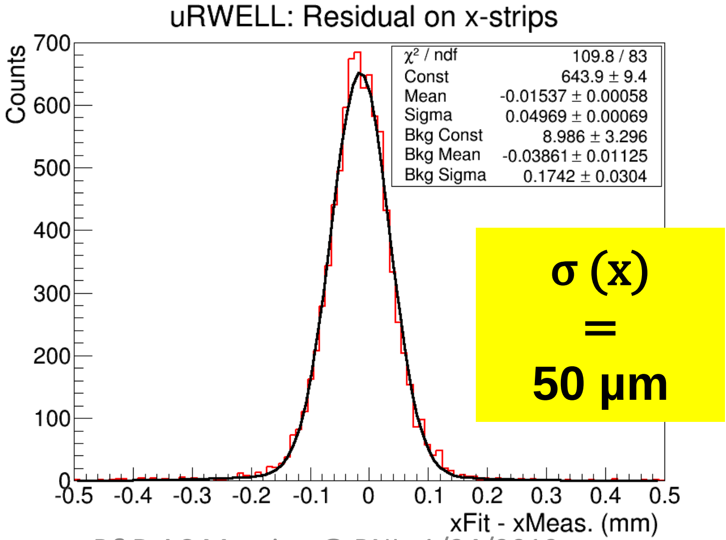


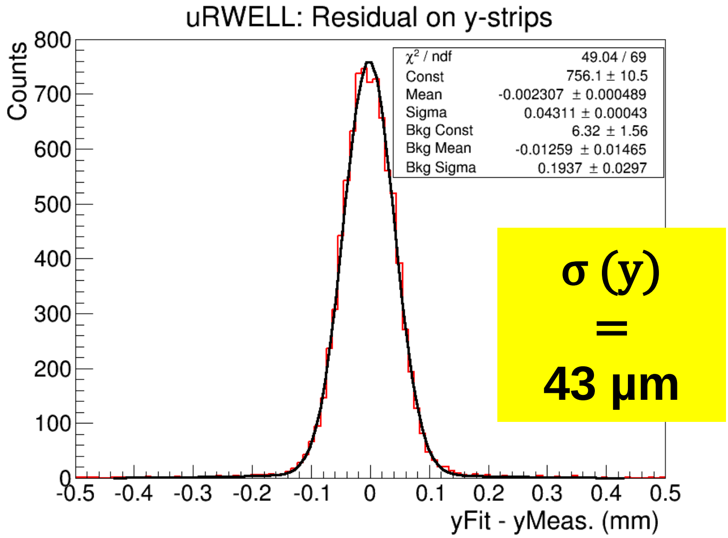
Hole pitch 140um

Hole diameter 70um on top 40um bot

Read-out line pitch 400um X and Y

Track fit residual distributions from FNAL test beam data





Progress @ UVA: Plans and Milestones

❖ Plans

- ⇨ Continue / Complete the FNAL test beam data analysis for large GEM and µRWELL prototypes
- ⇨ Present the results at the coming MPGD2019 Conference in Paris
- ⇨ Characterization of the small µRWELL prototype, the high rate capabilities and charge sharing of the readout structure
- ⇨ Start the draft of the paper on Chromium GEMs and on the large GEM R&D effort for submission to NIM A or IEEE TNS
- ⇨ Pursue the collaborative effort with FIT and TU on simulation and design of cylindrical µRWELL

❖ Milestones for 2019

- ⇨ Jan - May: FNAL test beam data analysis
- ⇨ May – Dec : Draft of manuscripts and R&D on µRWELL for EIC central tracker

eRD6 Publication List: Breakdown per institute

❖ Brookhaven National Lab

1. B. Azmoun et.al., “A Study of a Minidrift GEM Tracking Detector”, IEEE Transactions on Nuclear Science, Vol. 63, No. 3 (2016) 1768-1776; https://doi.org/10.1109/TNS.2016.2550503.
2. C. Woody et.al., “A Prototype TPC/Cherenkov Detector with GEM Readout for Tracking and Particle Identification and its Potential Use at an Electron Ion Collider”; https://inspirehep.net/record/1409973/files/arXiv:1512.05309.pdf.
3. B. Azmoun et al.; “Initial studies of a short drift GEM tracking detector”, In: 2014 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC). Nov. 2014; https://doi.org/10.1109/NSSMIC.2014.7431059
4. M. L. Purschke et al. “Test beam study of a short drift GEM tracking detector“, In: 2013 IEEE Nuclear Science Symposium and Medical Imaging Conference (2013 NSS/MIC). Oct. 2013; https://doi.org/10.1109/NSSMIC.2013.6829463
5. B. Azmoun et al. “Design Studies for a TPC Readout Plane Using Zigzag Patterns with Multistage GEM Detectors”. In: IEEE Transactions on Nuclear Science (July 2018), pp. 1–1. issn: 0018-9499. doi: 10.1109/TNS.2018.2846403.
6. B. Azmoun, et al., “Results from a Prototype Combination TPC Cherenkov Detector with GEM Readout”, submitted for publication in IEEE Transactions on Nuclear Science, Dec. 2018.

❖ Florida Tech

1. M. Hohlmann et al. “Low-mass GEM detector with radial zigzag readout strips for forward tracking at the EIC“, In: 2017 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC 2017) Atlanta, Georgia, USA, October 21-28, 2017; http://inspirehep.net/record/1636290/files/arXiv:1711.05333.pdf
2. A. Zhang et al. “A GEM readout with radial zigzag strips and linear charge-sharing response“; In: Nucl. Instr. Meth. A, article in press (2017). arXiv: https://arxiv.org/abs/1708.07931v1
3. A. Zhang and M. Hohlmann, "Accuracy of the geometric-mean method for determining spatial resolutions of tracking detectors in the presence of multiple Coulomb scattering," JINST 11 P06012 (2016), June 21, 2016; https://doi.org/10.1088/1748-0221/11/06/P06012
4. A. Zhang et al. “R&D on GEM detectors for forward tracking at a future Electron-Ion Collider“, In: Proceedings, 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC 2015): San Diego, California, United States. 2016, p. 7581965; https://doi.org/10.1109/NSSMIC.2015.7581965
5. A. Zhang, et al., "Performance of a large-area GEM Detector read out with wide radial zigzag strips," Nucl. Inst. Meth. A 811 (2016) 30-41; https://doi.org/10.1016/j.nima.2015.11.157 EIC Detector R&D AC Meeting @ BNL, 1/18/2018 32 eRD6 Publication List: Breakdown per institute

eRD6 Publication List: Breakdown per institute

❖ INFN Trieste

1. J. Agarwala et al. “Optimized MPGD-based Photon Detectors for high momentum particle identification at the Electron-Ion Collider”. In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment (2018). issn: 0168-9002. doi: https://doi.org/10.1016/j.nima.2018.10.185. url: http://www.sciencedirect.com/science/ article/pii/S0168900218314992.
2. J. Agarwala et al. “Novel NanoDiamond based photocathodes for gaseous detectors”. In: 2018. arXiv: 1812.04552 [physics.ins-det].

❖ Stony Brook University

1. M. Blatnik et al., “Performance of a Quintuple-GEM Based RICH Detector Prototype”, In: IEEE Trans. Nucl. Sci. 62.6 (2015), https://doi.org/10.1109/TNS.2015.2487999

❖ Temple University

1. M. Posik and B. Surrow. “Construction of a Triple-GEM Detector Using Commercially Manufactured Large GEM Foils”. In: 2018. arXiv: 1806.01892 [physics.ins-det].
2. M. Posik and B. Surrow. “Construction of Triple-GEM Detectors Using Commercially Manufactured Large GEM Foils”. In: Proceedings, 2016 IEEE Nuclear Science Symposium and Medical Imaging Conference: NSS/MIC 2016: Strasbourg, France. 2016, p. 8069743. doi: 10 . 1109 / NSSMIC . 2016 . 8069743. arXiv: 1612.03776 [physics.ins-det].
3. M. Posik and B. Surrow. “Optical and electrical performance of commercially manufactured large GEM foils”. In: Nucl. Instrum. Meth. A802 (2015), pp. 10–15. doi: 10.1016/j.nima.2015.08.048. arXiv: 1506.03652 [physics.ins-det].
4. M. Posik and B. Surrow. “R&D of commercially manufactured large GEM foils”. In: Proceedings, 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC 2015): San Diego, California, United States. 2016, p. 7581802. doi: 10.1109/NSSMIC.2015.7581802. arXiv: 1511.08693 [physics.ins-det]. 52
5. M. Posik and B. Surrow. “Research and Development of Commercially Manufactured Large GEM Foils”. In: Proceedings, 21st Symposium on Room-Temperature Semiconductor X-ray and Gamma-ray Detectors (RTSD 2014): Seattle, WA, USA, November 8-15, 2014. 2016, p. 7431060. doi: 10.1109/ NSSMIC.2014.7431060. arXiv: 1411.7243 [physics.ins-det].

eRD6 Publication List: Breakdown per institute

❖ Univ. of Virginia

1. K. Gnanvo et al., “Performance in Test Beam of a Large-area and Light-weight GEM detector with 2D Stereo-Angle (U-V) Strip Readout”, Nucl. Inst. and Meth. A808 (2016); https://doi.org/10.1016/j.nima.2015.11.071
2. K. Gnanvo, et al. “Large Size GEM for Super Bigbite Spectrometer (SBS) Polarimeter for Hall A 12 GeV program at JLab”, Nucl. Inst. and Meth. A782, 77-86 (2015); https://doi.org/10.1016/j.nima.2015.02.017

❖ Yale University

1. S. Aiola et al., “Combination of two Gas Electron Multipliers and a Micromegas as gain elements for a time projection chamber”, Nucl. Inst. and Meth. A834 (2016); https://doi.org/10.1016/j.nima.2016.08.007

~22 eRD6 publications in all, with more to come!!

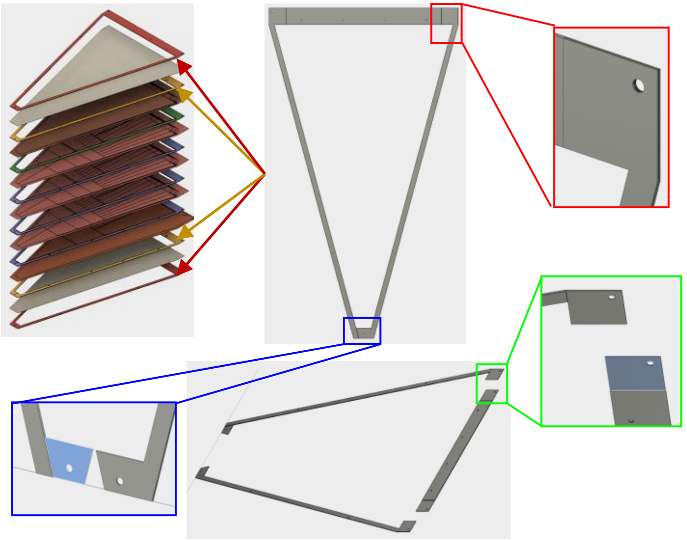
Thank you!

Backup

Progress @ UVA: Low Cost Support Frames

Outer Frames without spacer grids: Low cost

- **Four Outer Frames** for gas window foils without spacers grid
- Each frame made of four **G10** pieces cut out in local machine shop
- Low material and production cost

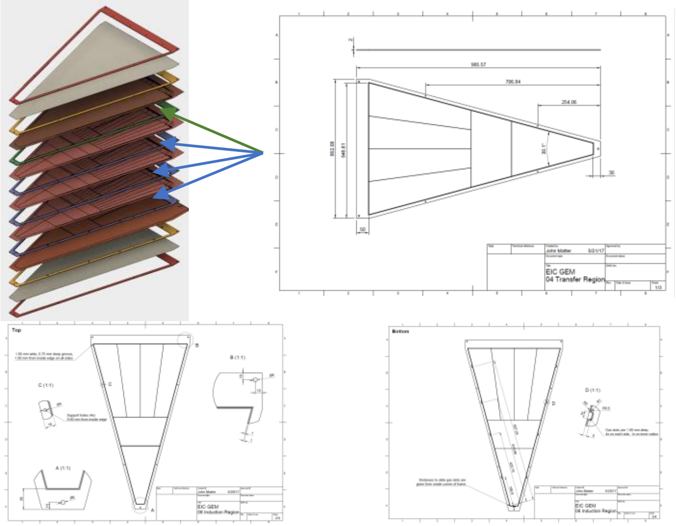


Set of G10 pieces for all 4 frames

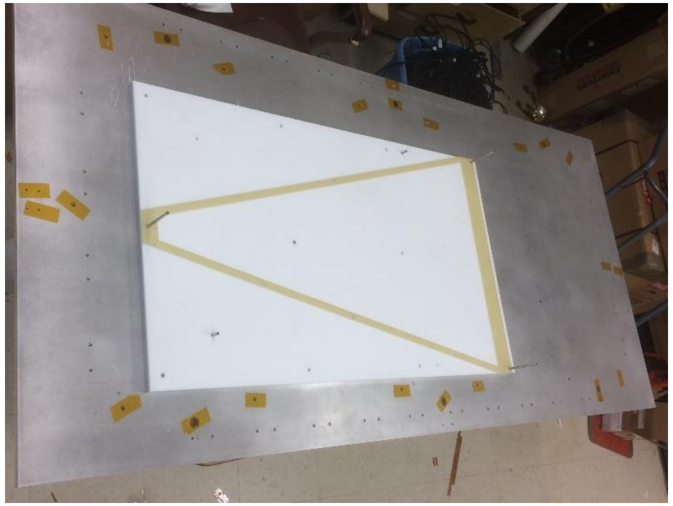
Set for one frame

Inner Frames for GEMs with spacer grids: High cost

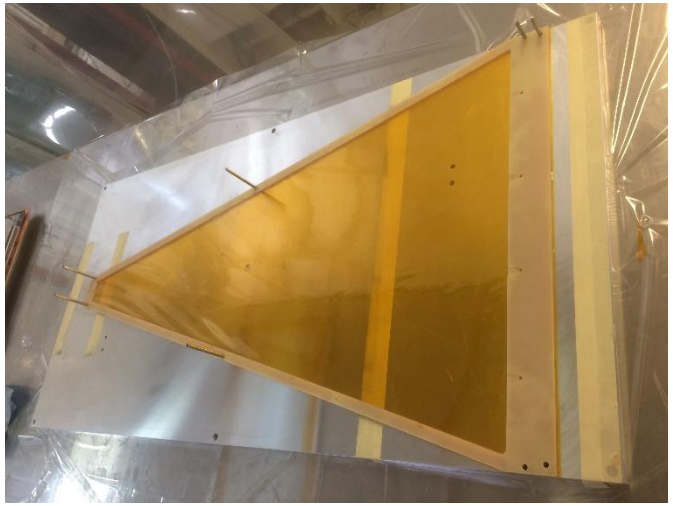
- **Four Inner Frames** with 300 µm spacers grid for GEM foils
- Precision machining of **PERMAGLAS** by RESARM (Belgium)
- High material and machining cost



Gluing of one frame

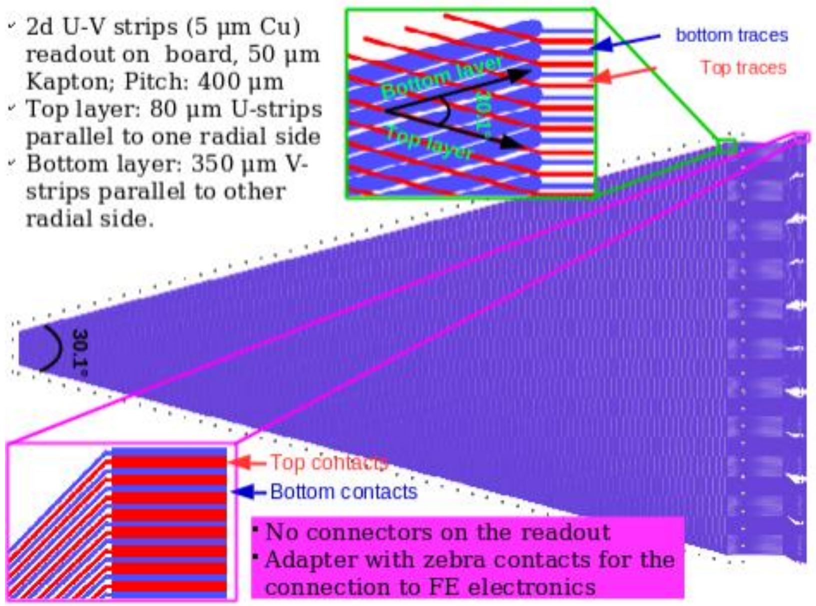


Window foil glued to low cost frames

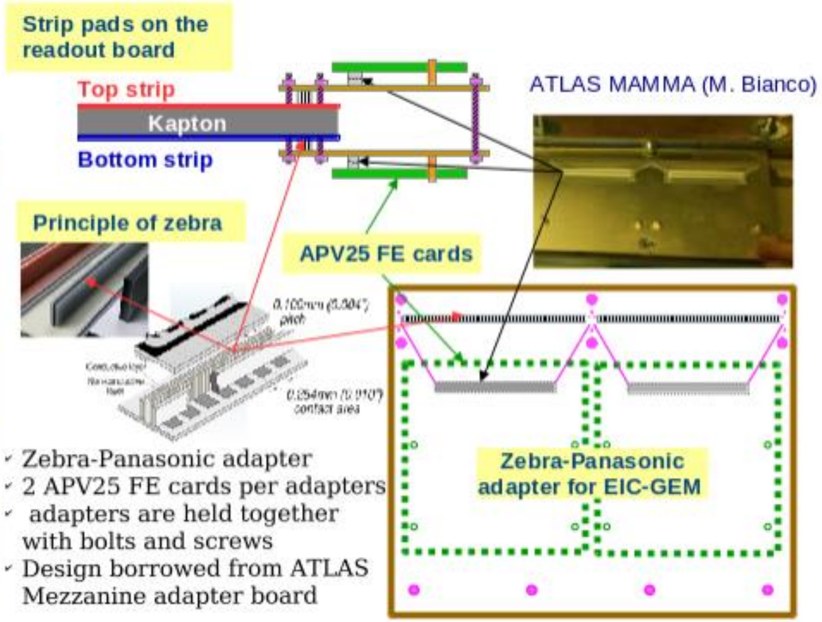


Progress @ UVA: U-V Readout with Zebra Connection

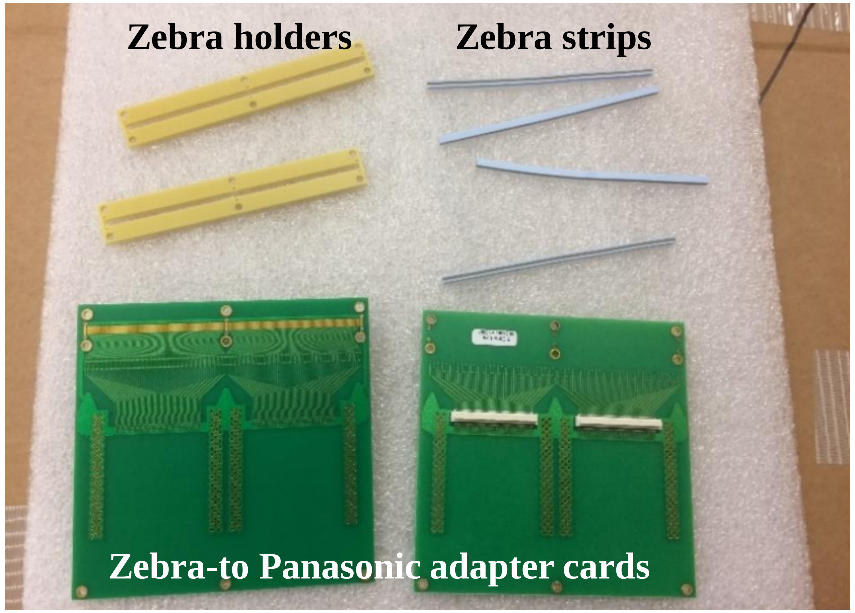
Design of EIC-Proto II 2D U-V strips readout board



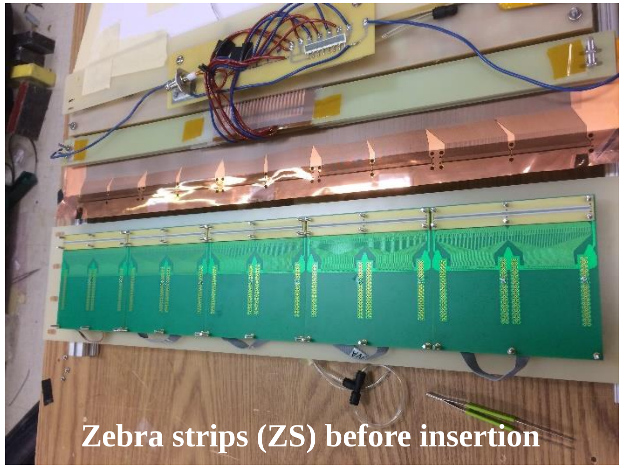
Drawings of the Zebra-Panasonic adapter board

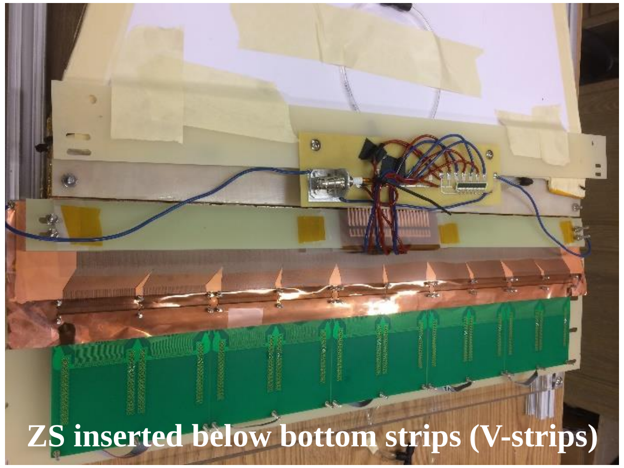


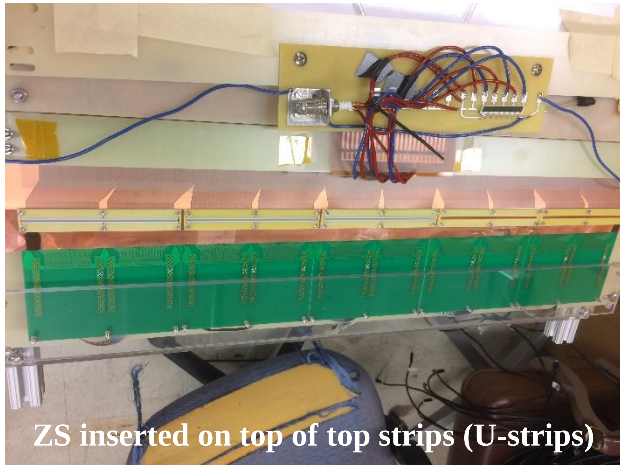
Components of the double-sided zebra connection



Assembly steps of the double-sided zebra connection scheme on the large GEM prototype


Zebra strips (ZS) before insertion


ZS inserted below bottom strips (V-strips)


ZS inserted on top of top strips (U-strips)


APV25 FE cards for top strips (U-strips)